Introduction to cloud physics and weather modification

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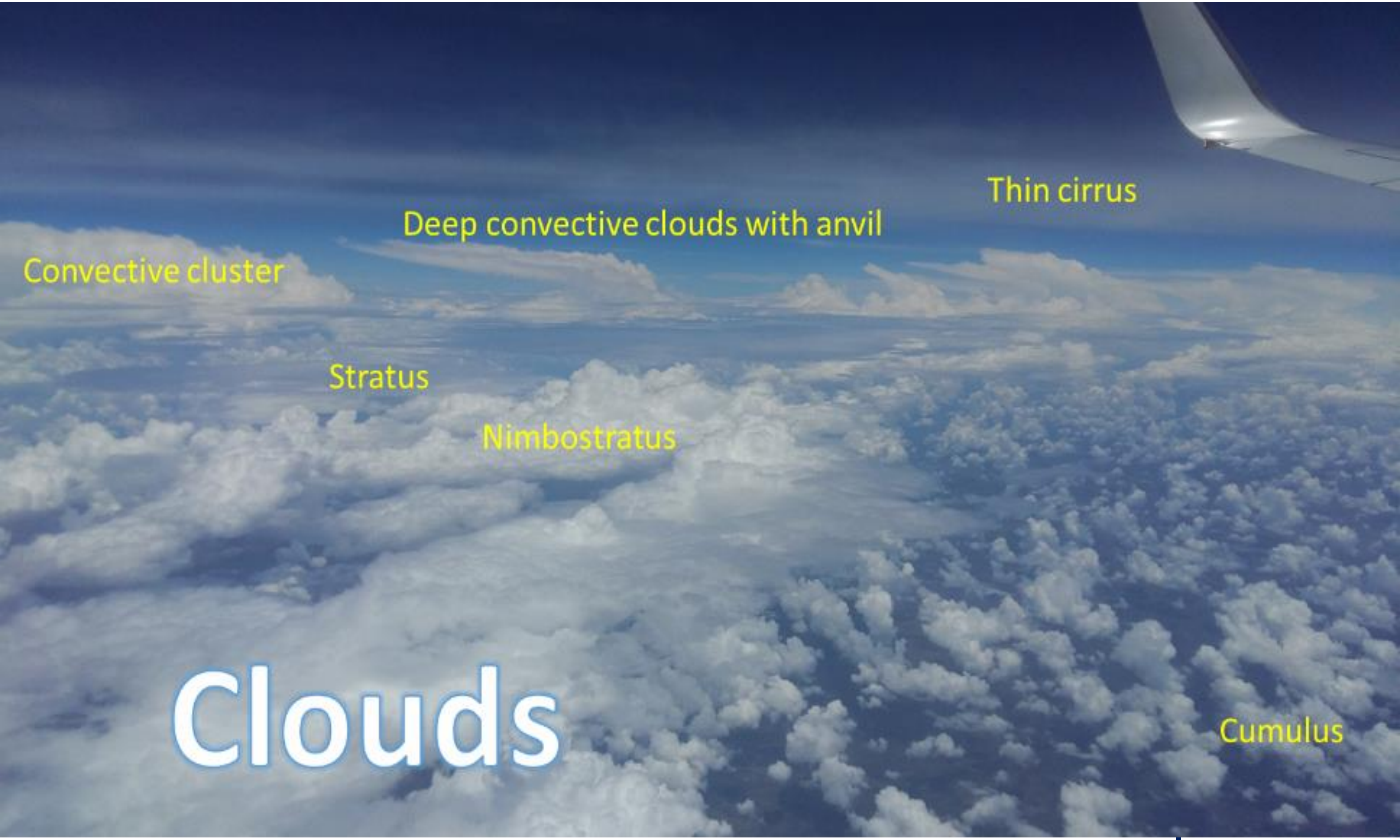
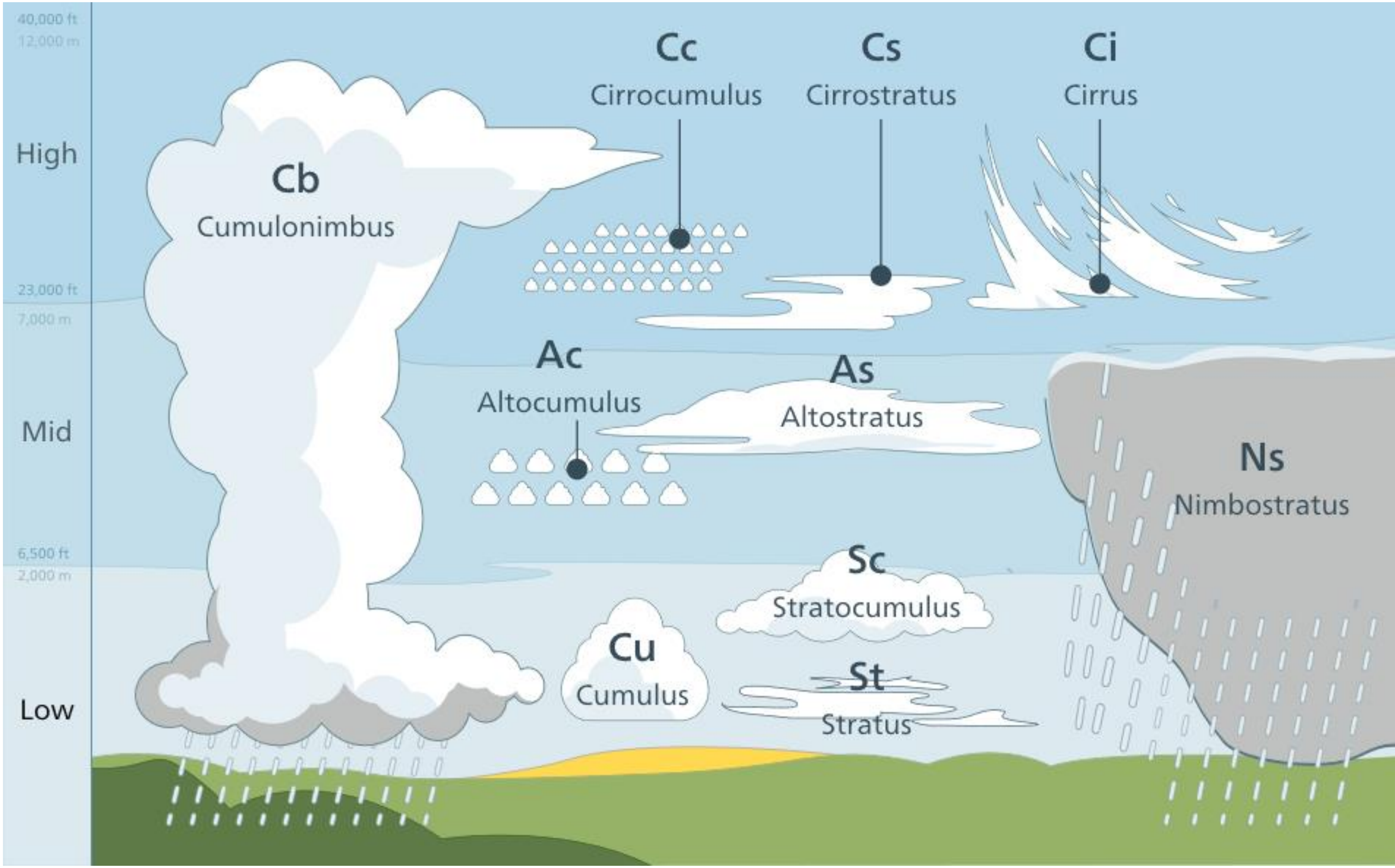
also contributed to the lecture content

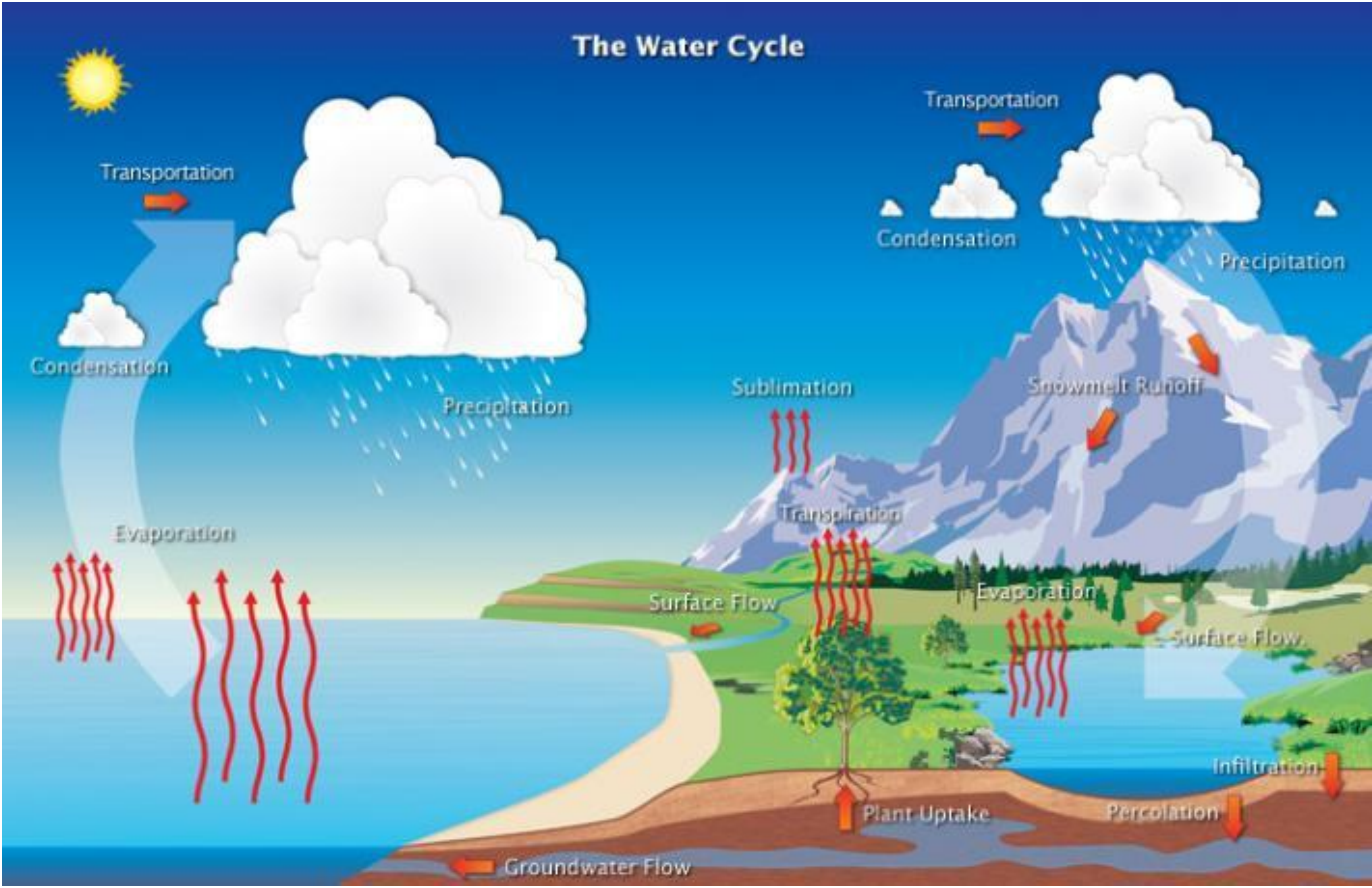

Thin cirrus
Deep convective clouds with anvil
Convective cluster
Stratus
Nimbostratus
Clouds
Cumulus

There are different cloud types in the atmosphere



Classification of clouds by altitude (Bruyn, 2012)

Clouds are important component of water cycle

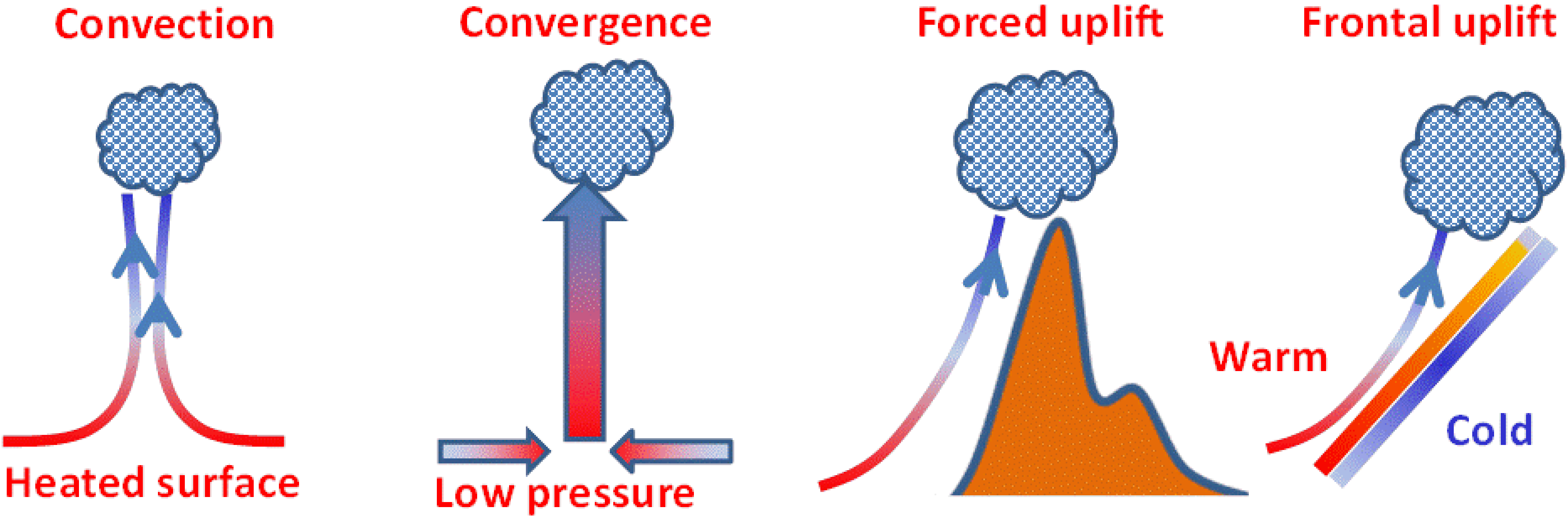


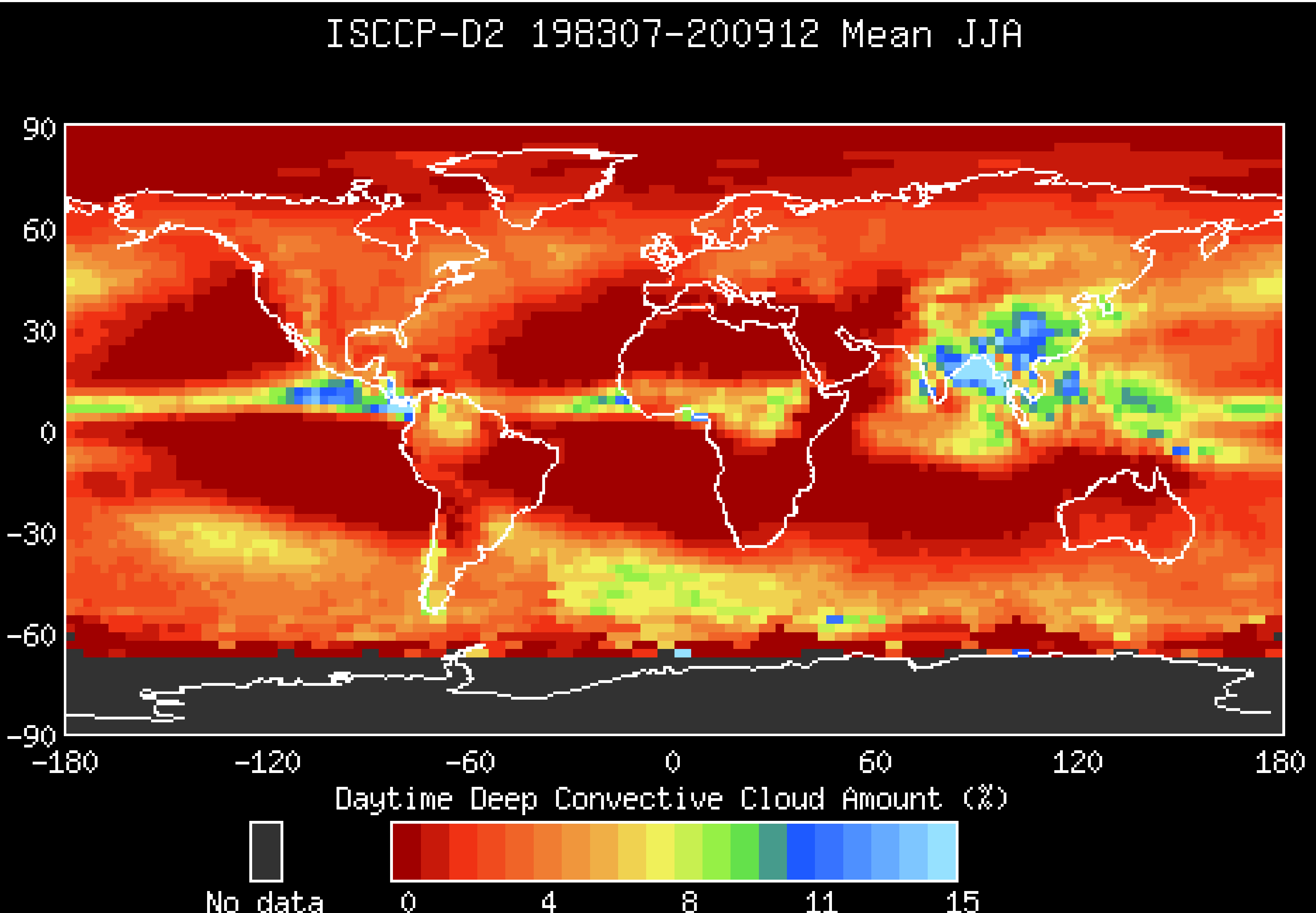
Source: NOAA National Weather Service Jetstream.

Why Clouds are important

- ✓ Generate precipitation (liquid/ice)
- ✓ Impact radiation and energy and water balance
- ✓ Cool the earth surface
- ✓ Reflect radiation back to space
- ✓ Warm the atmosphere
- ✓ Moisten the atmosphere
- ✓ Process aerosol particles
- ✓ Cleanse atmosphere ….
- ✓ Prime importance for Water resources

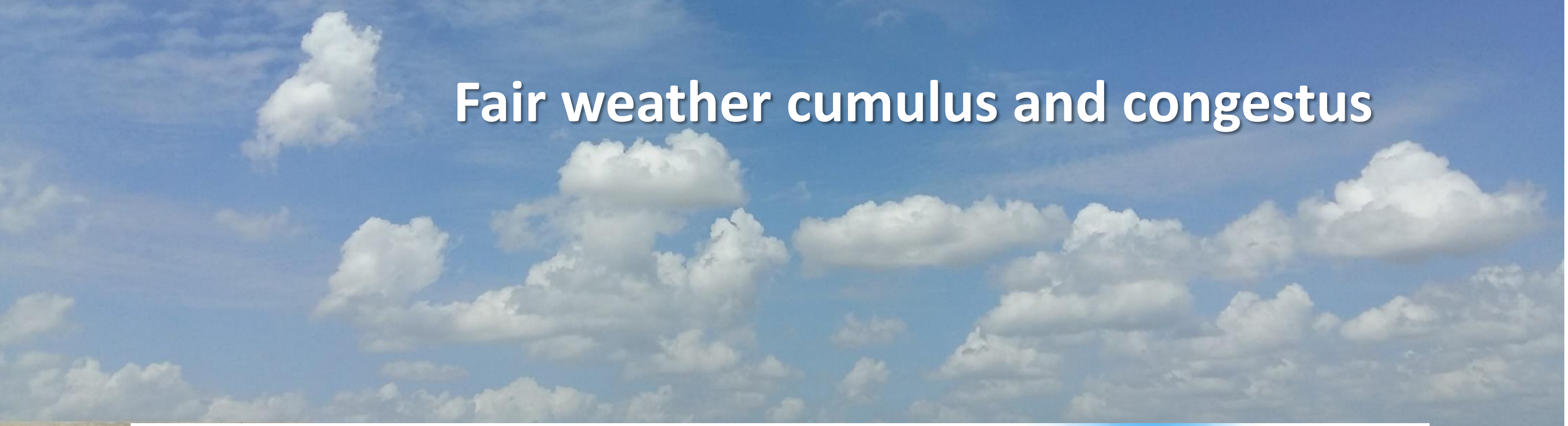
How do clouds form ?

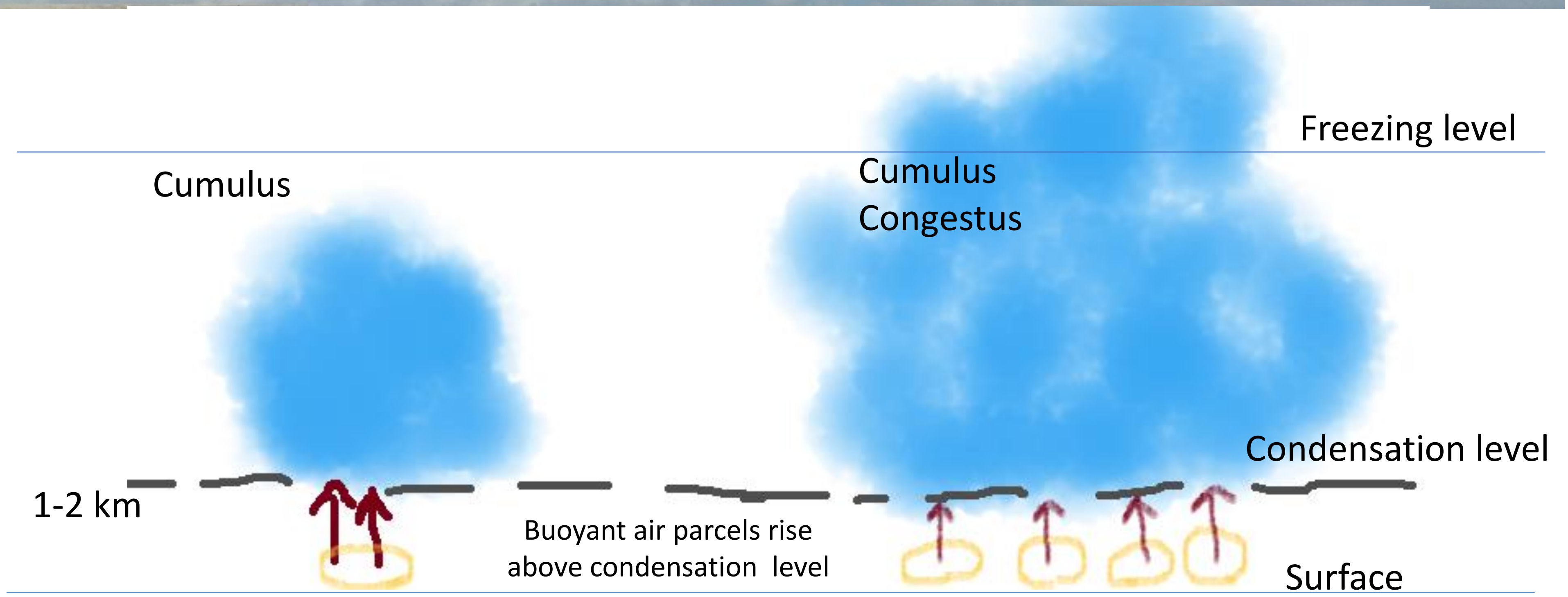




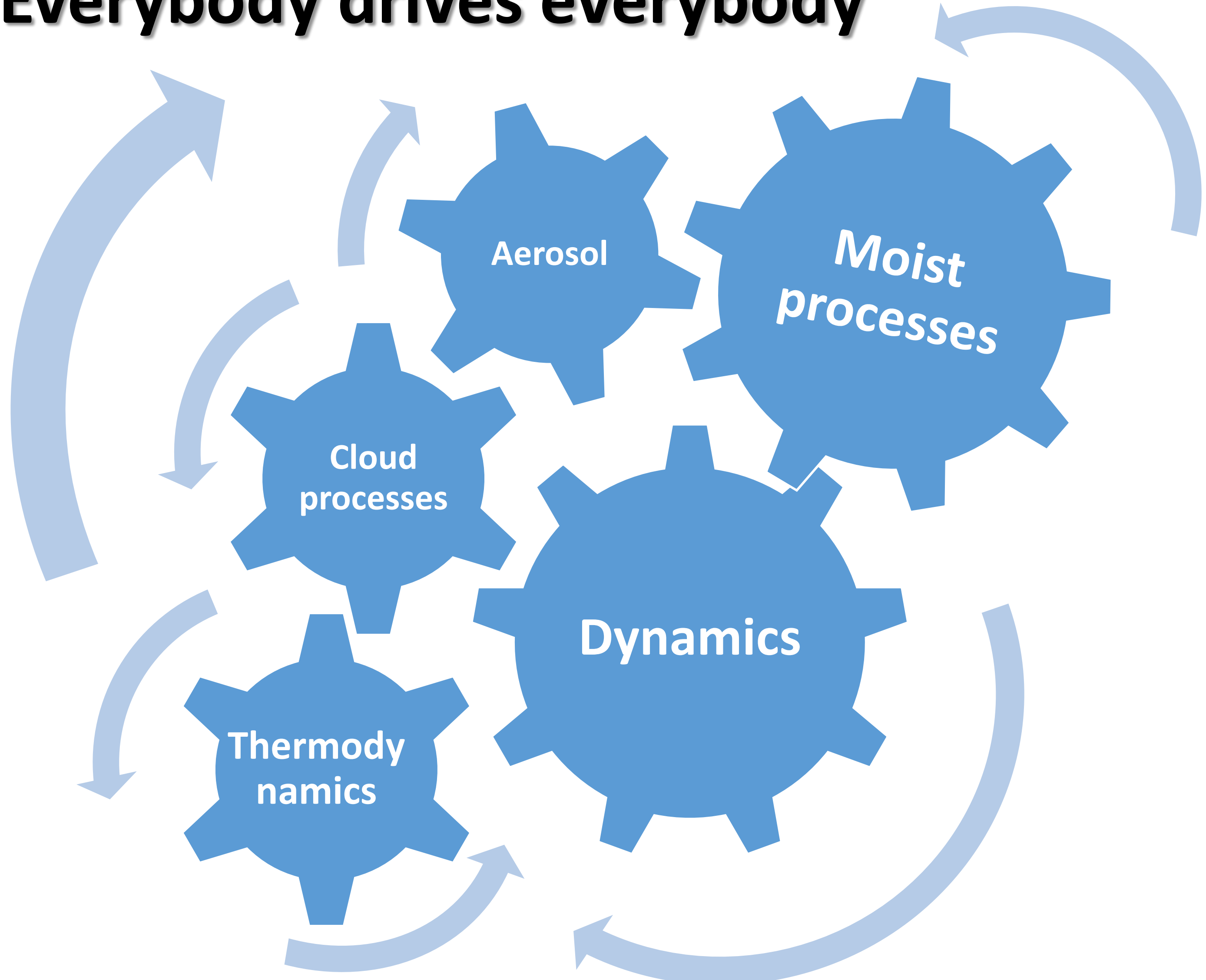
http://isccp.giss.nasa.gov/products/browsed2.html

Fair weather cumulus and congestus

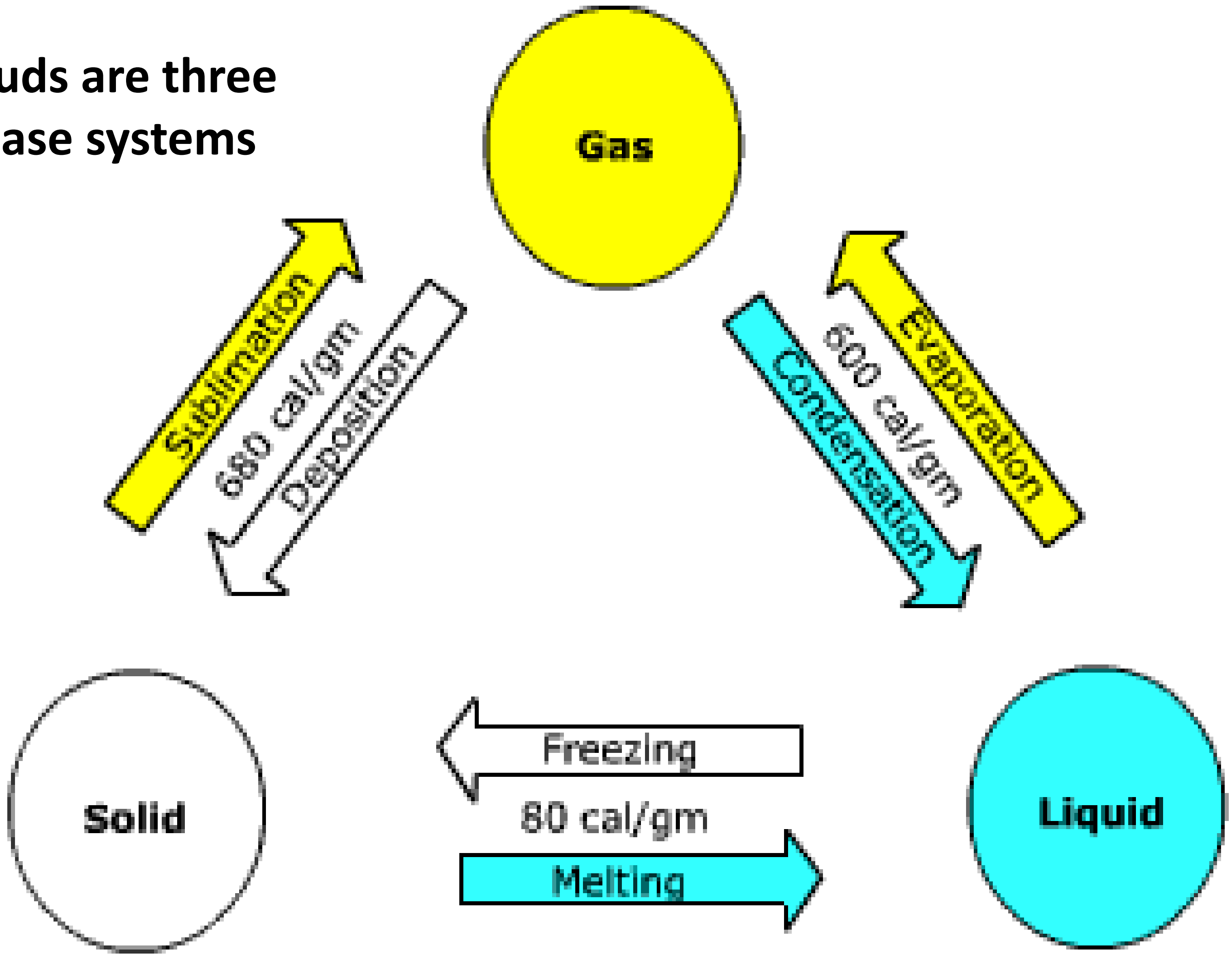




Problem: Everybody drives everybody

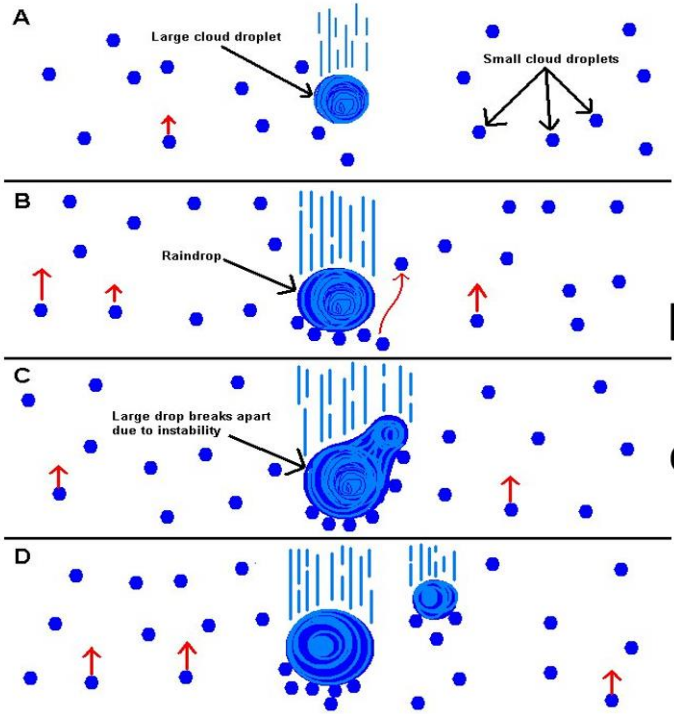


Clouds are three phase systems



Rain drop formation

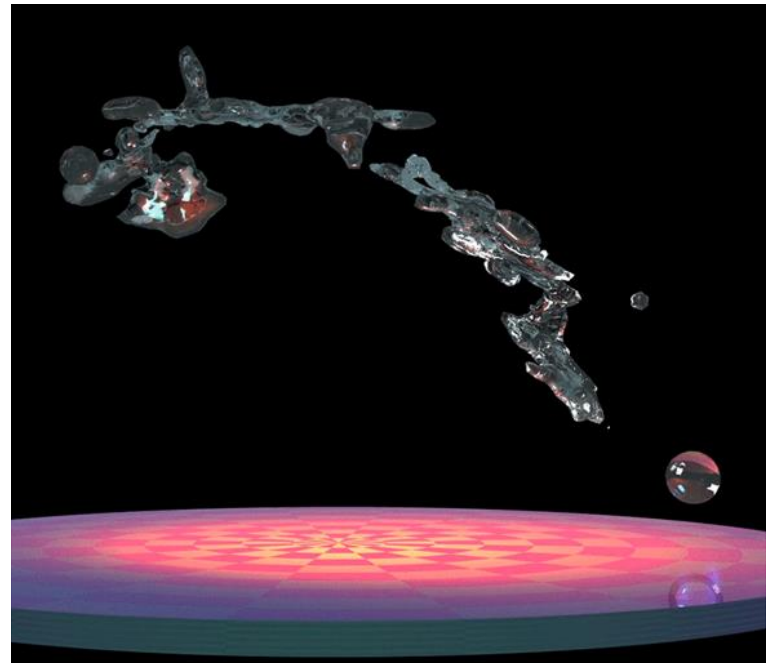
Growth of droplets Collision coalescence



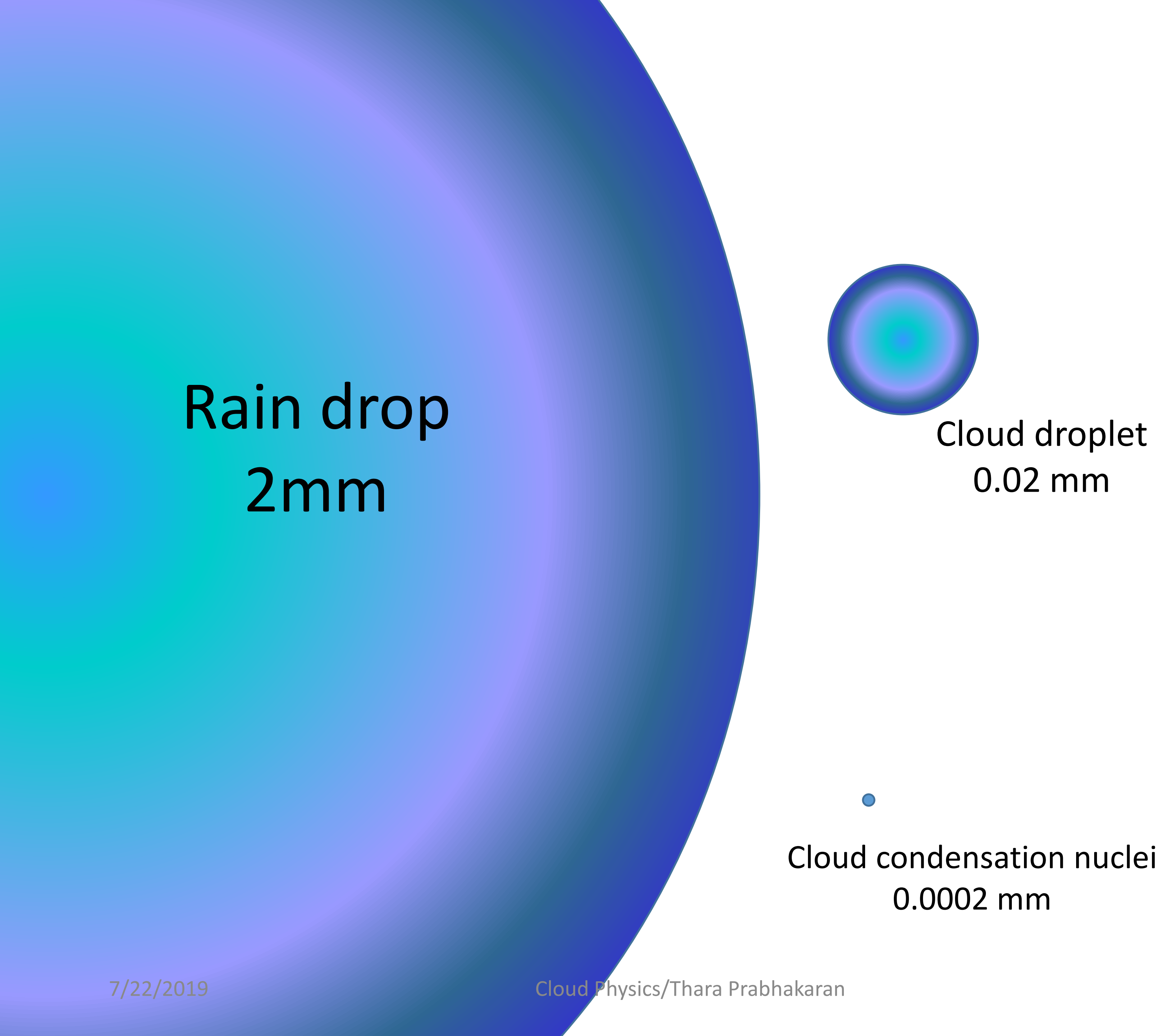
Raindrop forms

Falling large cloud drop collide and coalesce

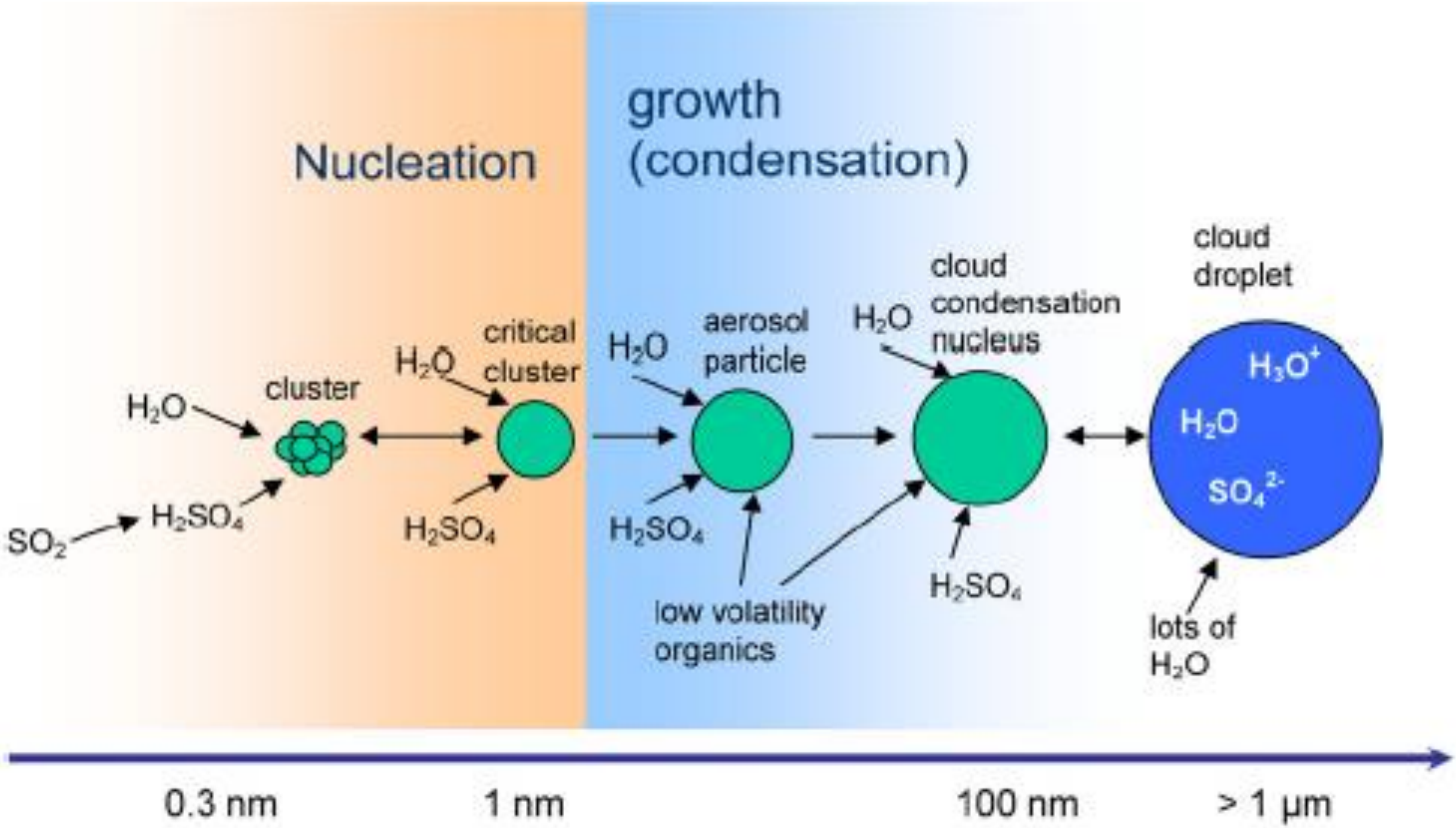
Growth of ice and Melting of ice



Cloud grows above freezing level, mixed phase (water + ice) process become important in contributing to precipitation.

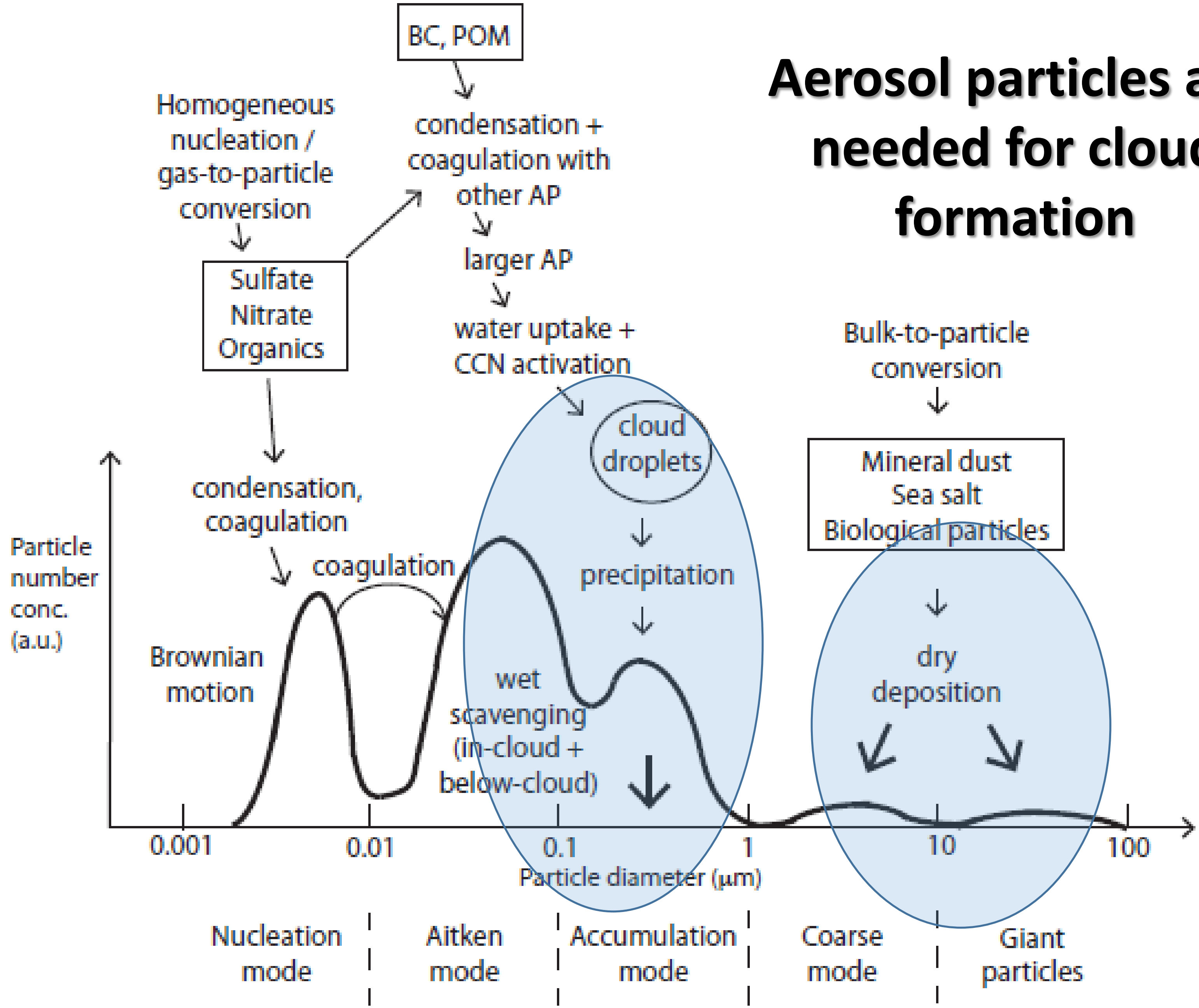

Rain drop
2mm
Cloud droplet
0.02 mm
Cloud condensation nuclei
0.0002 mm

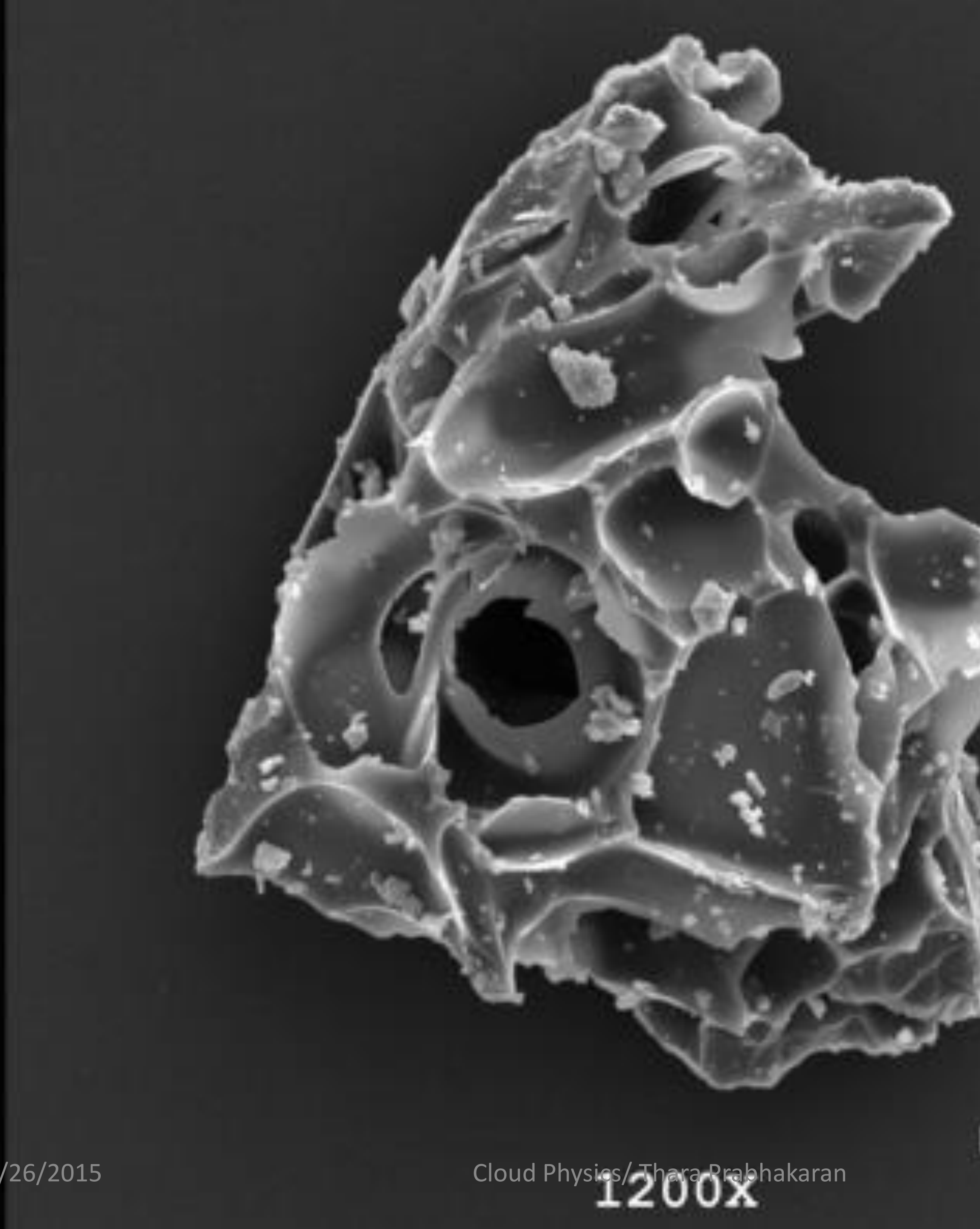
What happens when water vapour condenses ?



Curtius,2006

Aerosol particles are needed for cloud formation




20 µm
1200x


USGS

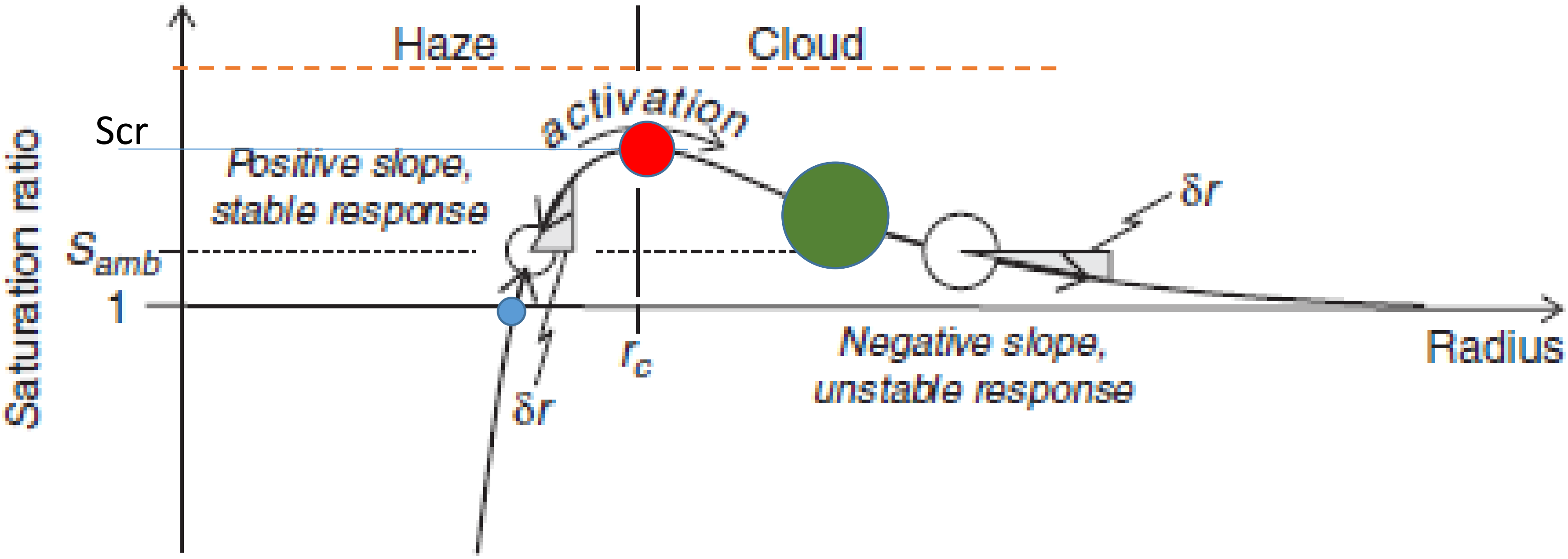
Facts on CCN

-Land is a source for CCN (high over land and low over ocean)
-Dust is not a dominant CCN (however the adsorption properties can make it a CCN- can swell)
-Clay is CCN active
-forest fires are source of CCN
-fossil fuel emissions (CCN at 1 % SS)

Arctic clean air CCN concentration is ≈ 30 cc while in continental air it could be 3000 cc

CCN/CN=0.2-0.6 in marine air
CCN/CN =<0.01 to 0.1 continental air – due to nonactivated small particles at low SSin large number

CCN activation

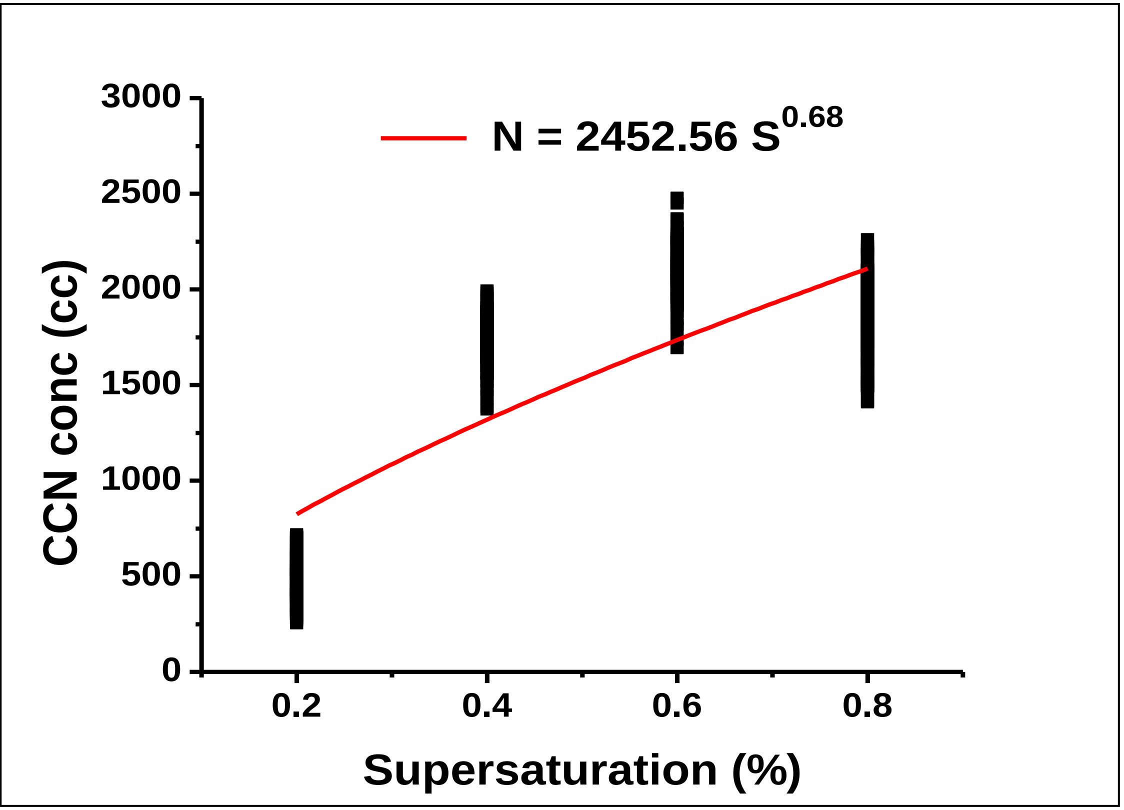


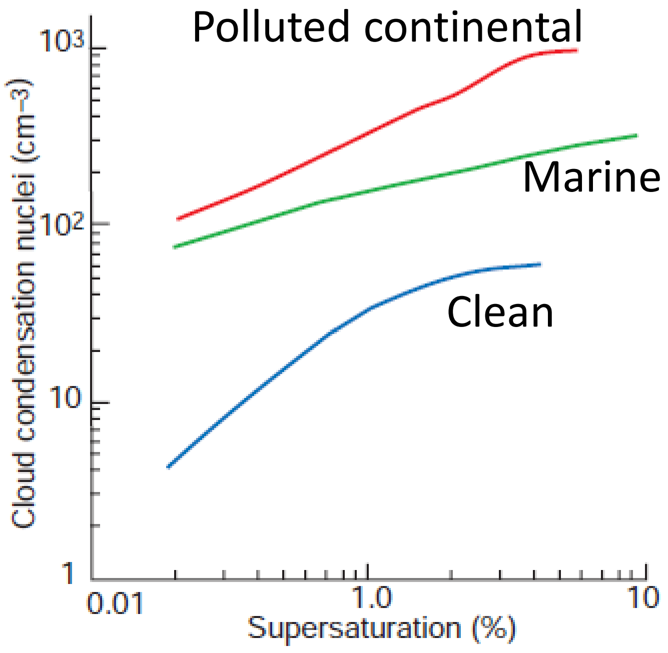
Consider a air parcel
CCN are chemically same and have same dry mass, they have same Kohler curve

The Scr is approx. 0.001 to 0.1 and the Accuracy needed for this observation are very high and is not observable

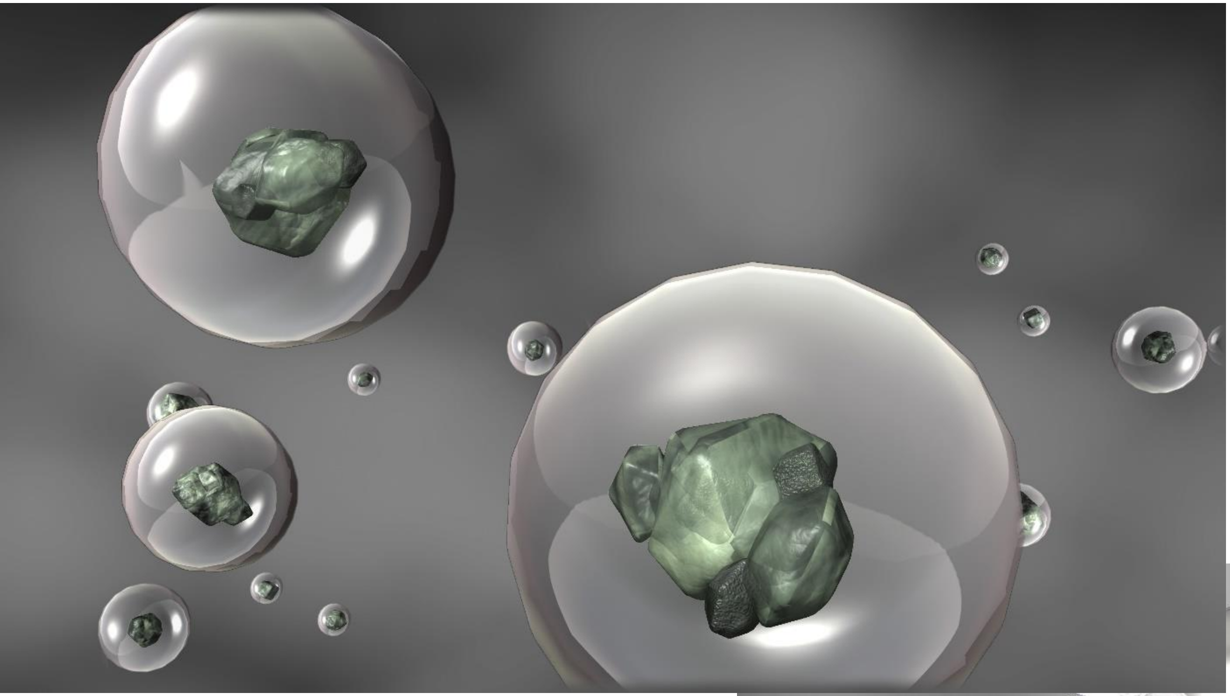
$$N = CS^k$$

CCN spectra



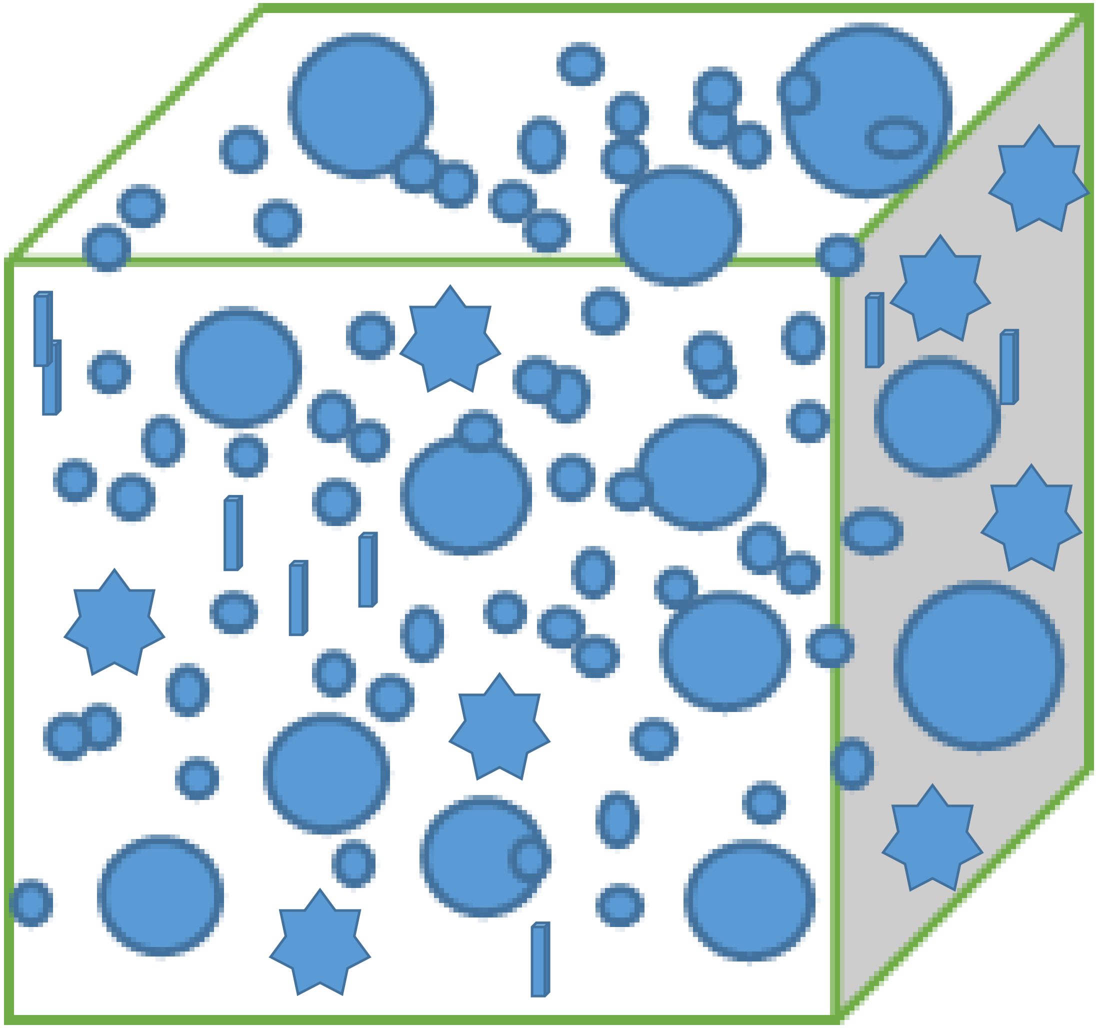


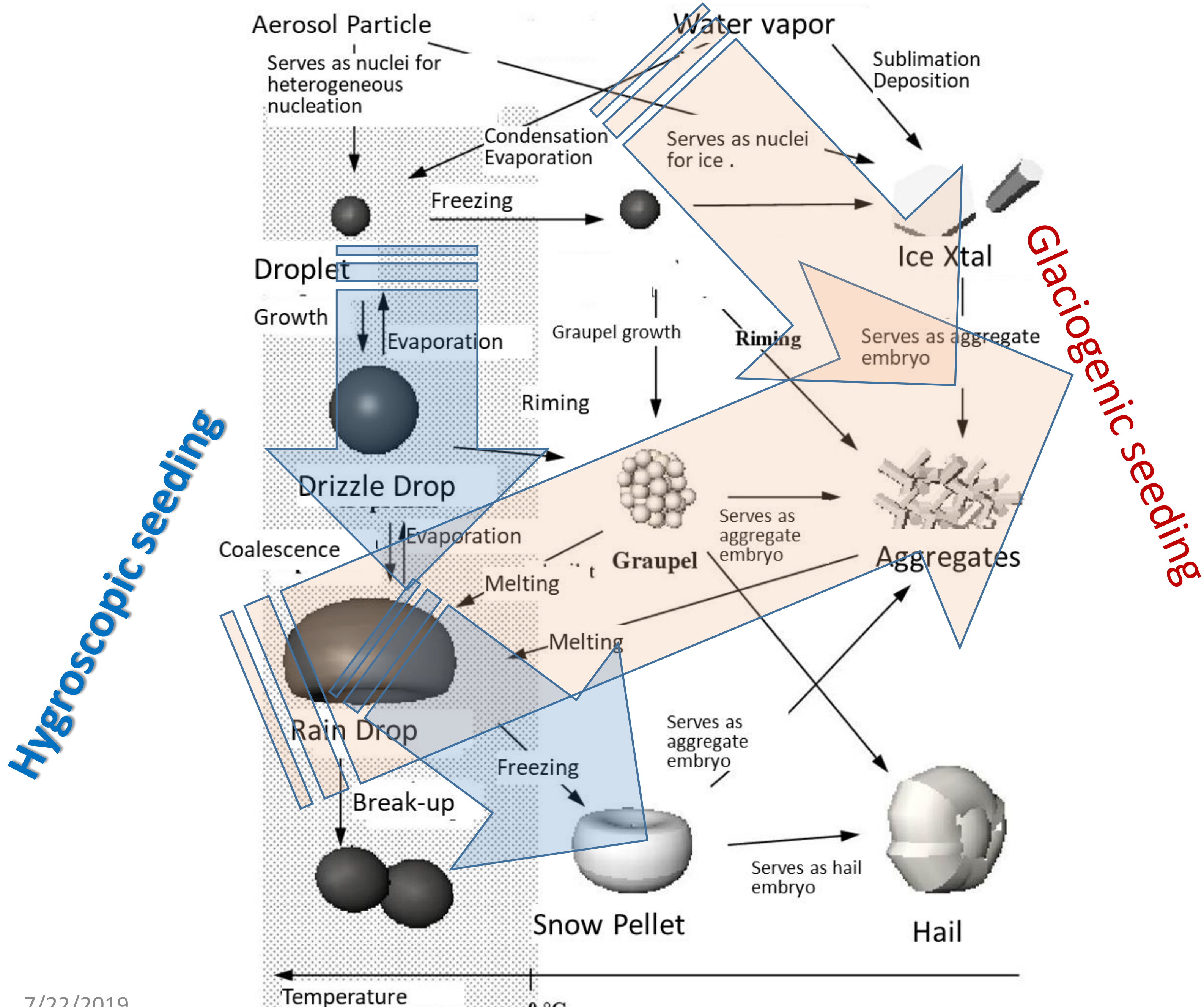
'N' is the CCN number concentration at any supersaturation'S'
'C' is the number concentration at 1% SS k the slope.



Source: NASA

We consider cloud droplets or ice particles in a cubic cm



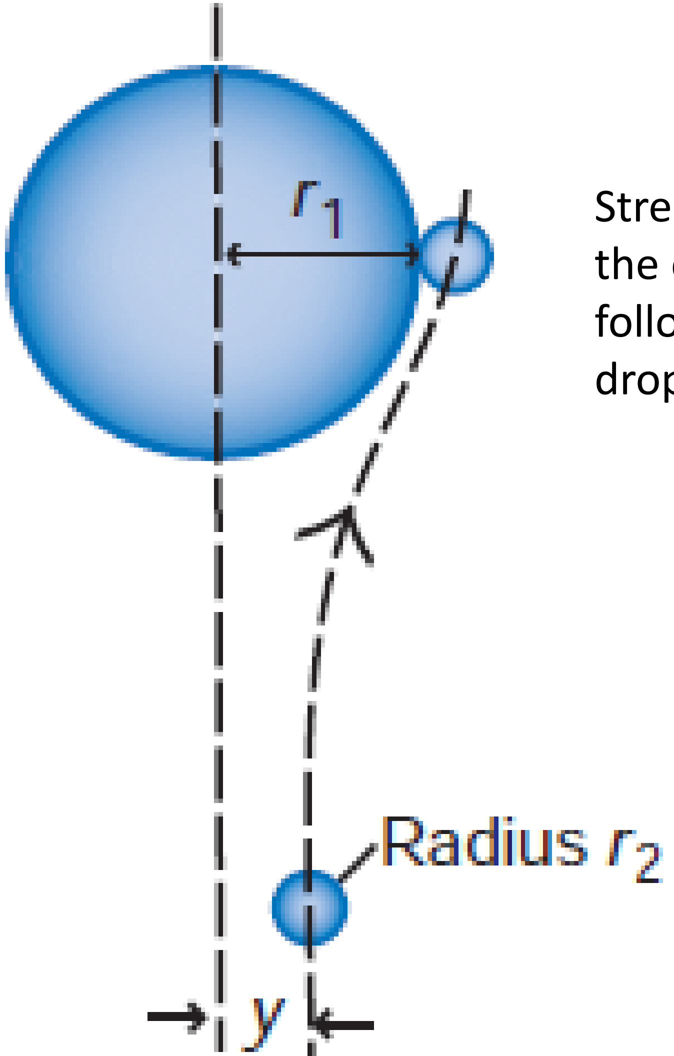

Aerosol Particle
Water vapor
Serves as nuclei for heterogeneous nucleation
Condensation
Evaporation
Sublimation
Deposition
Serves as nuclei for ice .
Freezing
Droplet
Ice Xtal
Growth
Evaporation
Graupel growth
Riming
Serves as aggregate embryo
Riming
Drizzle Drop
Evaporation
Coalescence
Graupel
Serves as aggregate embryo
Aggregates
Melting
Melting
Rain Drop
Freezing
Serves as aggregate embryo
Break-up
Snow Pellet
Serves as hail embryo
Hail
Temperature
0 °C
Hygroscopic seeding
Glaciogenic seeding

Collisions

πy^2 – effective collision cross-section

$\pi(r1+r2)^2$ -geometrical collision cross-section

Collector drop

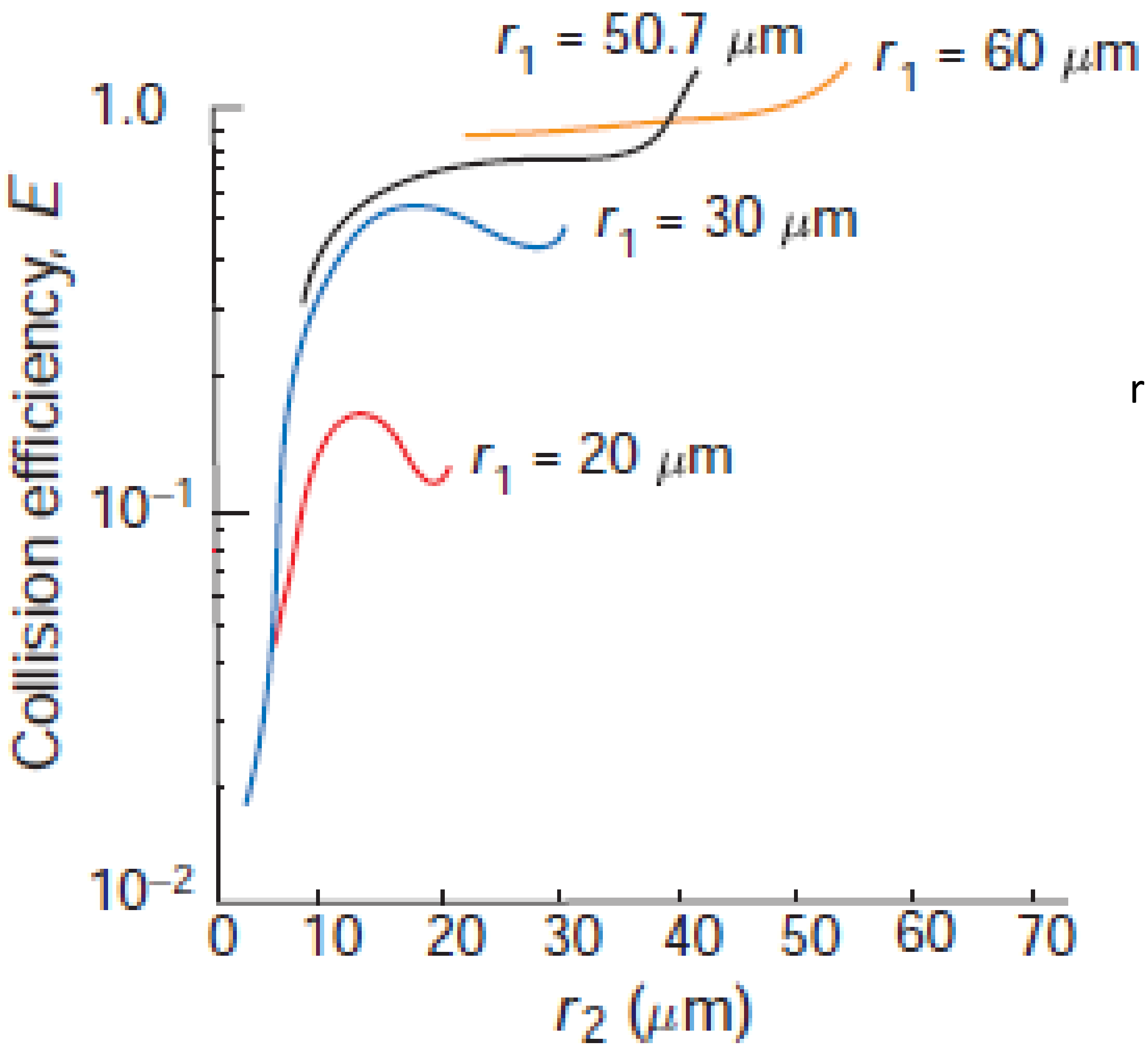


Streamline around the collector drop followed by small drop

Collision efficiency

$$E = \frac{y^2}{(r_1 + r_2)^2}$$

Collision efficiencies



Follows Streamlines

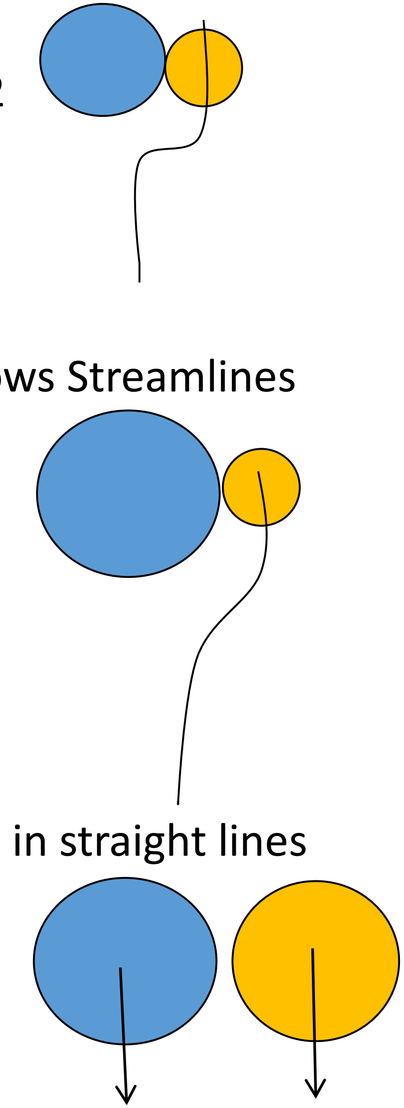
r1>r2

Follows Streamlines

r1>>r2

Moves in straight lines

r1=r2



Wake effects

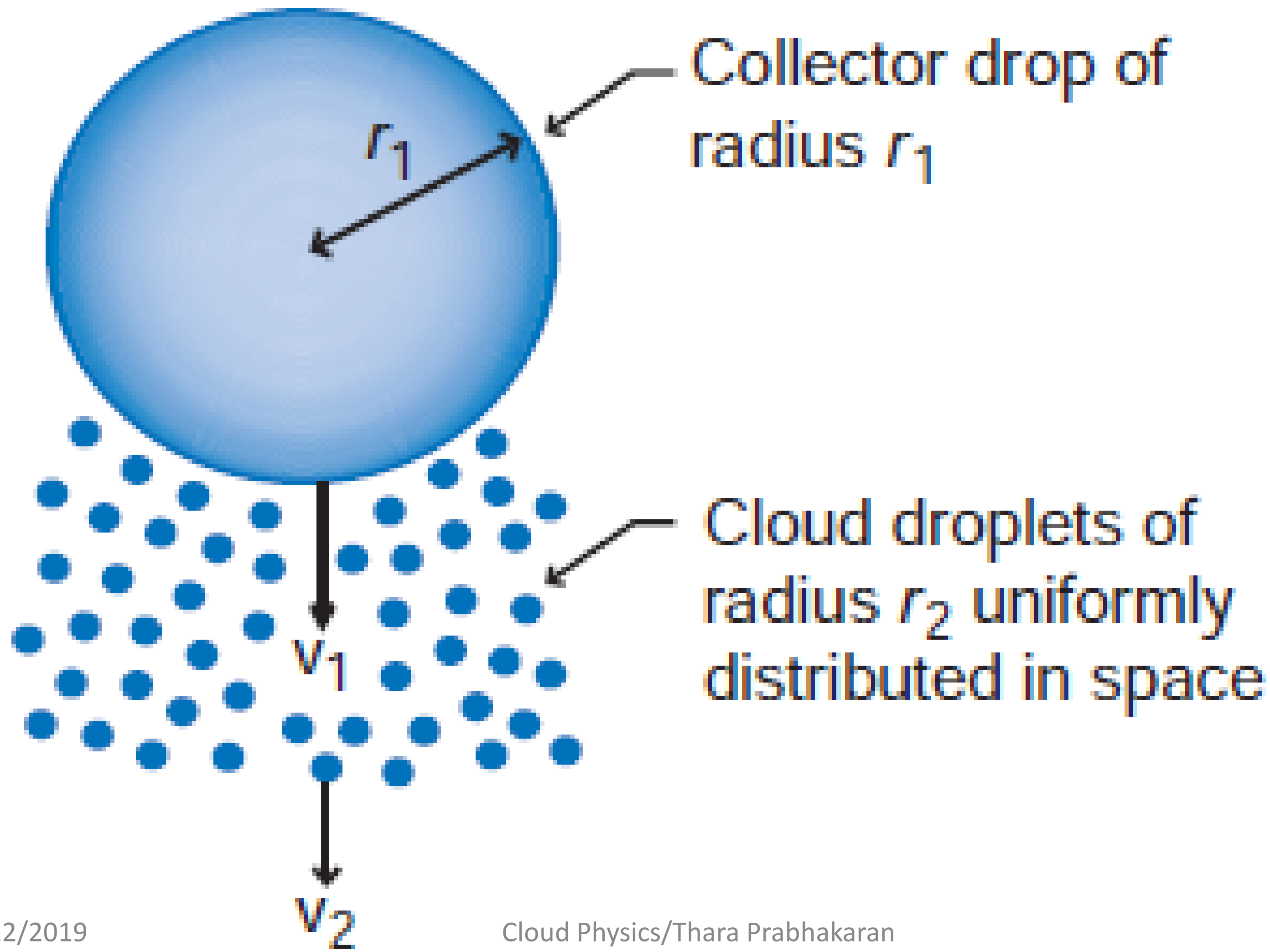
Collection

Fall velocities

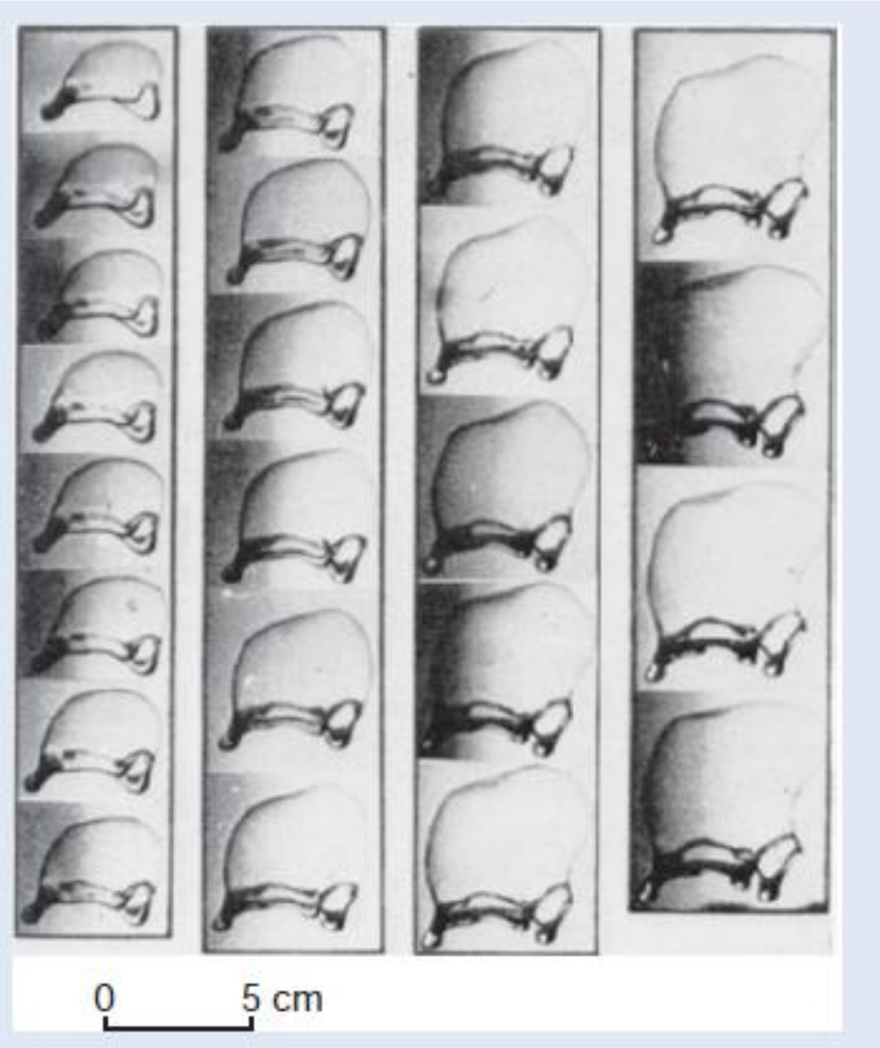
$$\frac{dM}{dt} = \pi r_1^2 (v_1 - v_2) w_l E_c$$

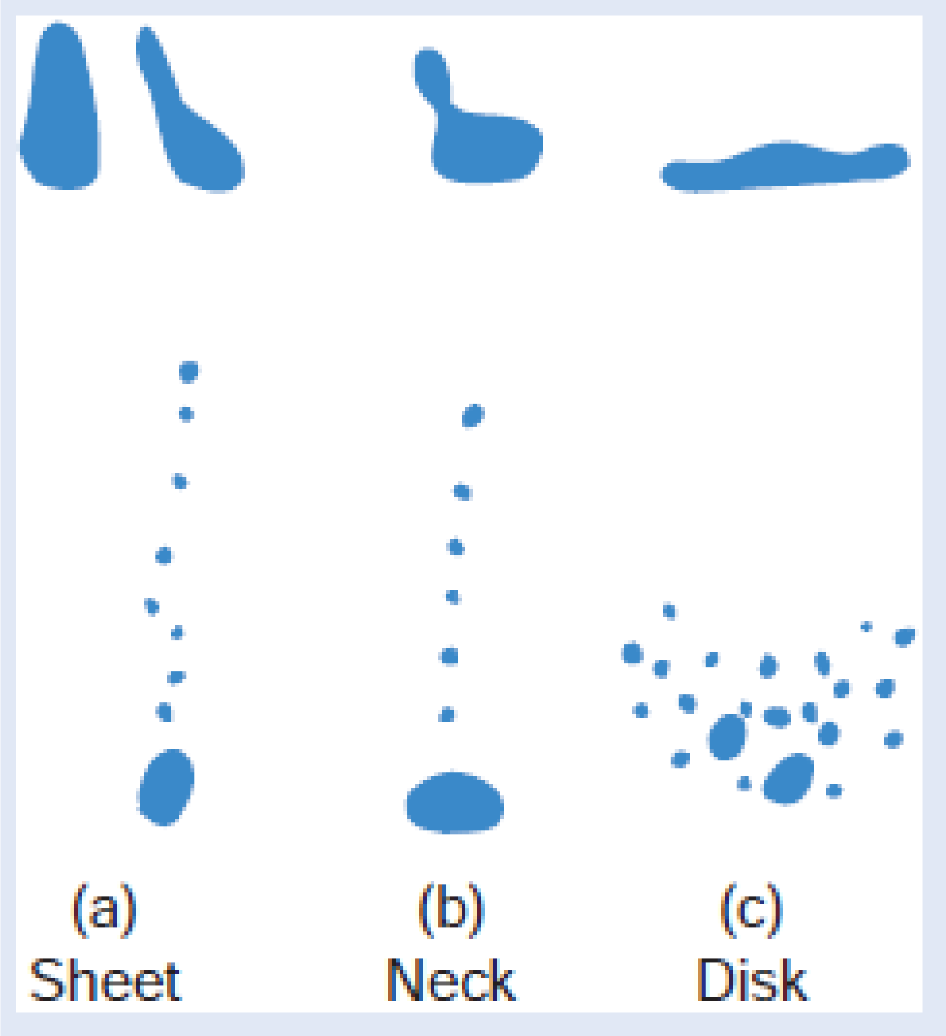
LWC

Collection efficiency



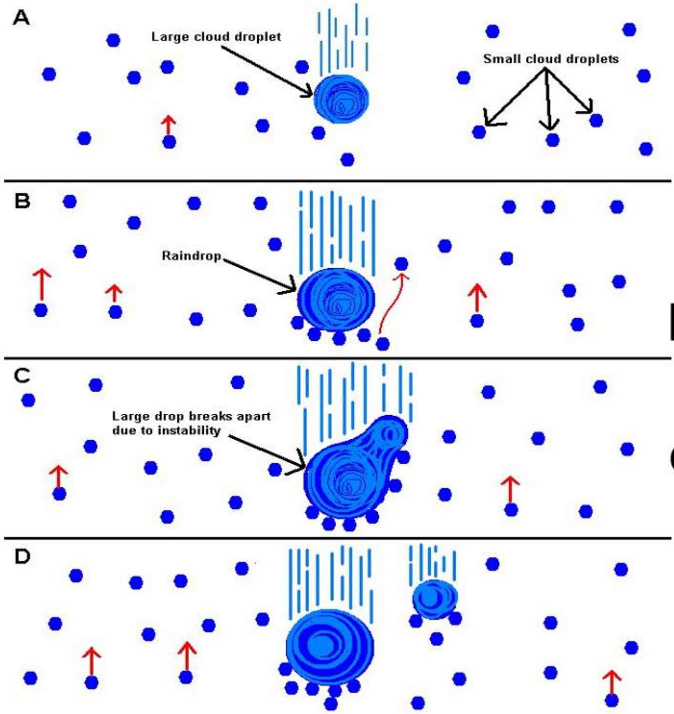
Breakup of raindrops





Rain drop formation

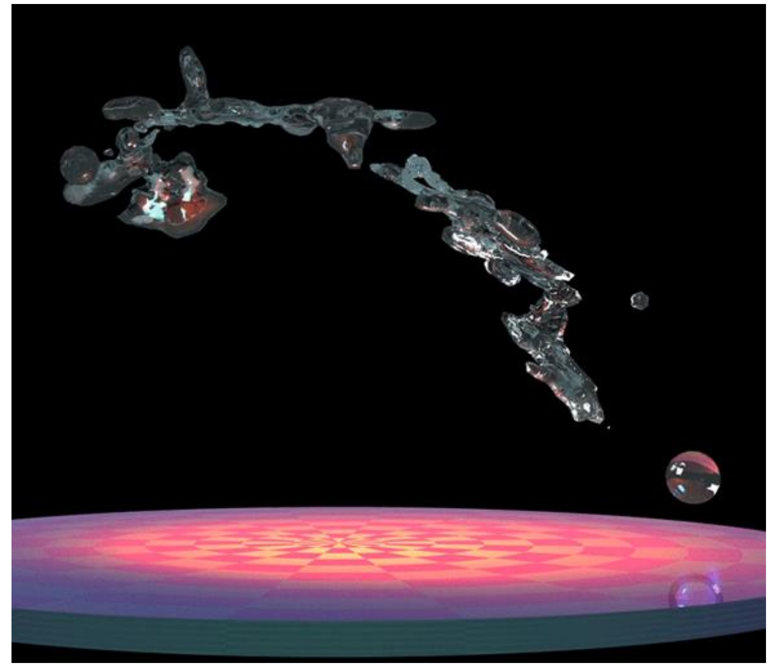
Growth of droplets Collision coalescence



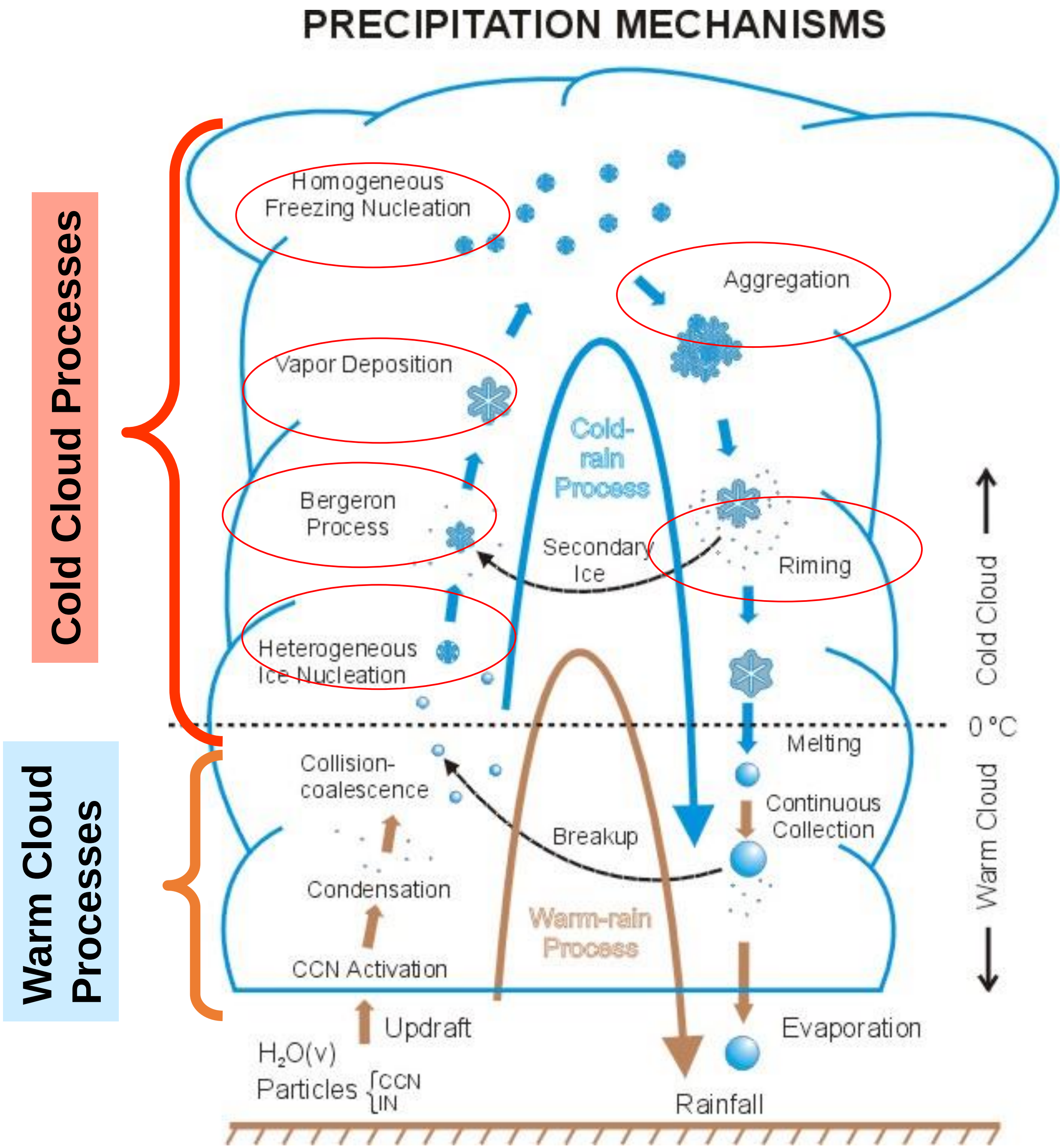
Raindrop forms

Falling large cloud drop collide and coalesce

Growth of ice and Melting of ice



Cloud grows above freezing level, mixed phase (water + ice) process become important in contributing to precipitation.



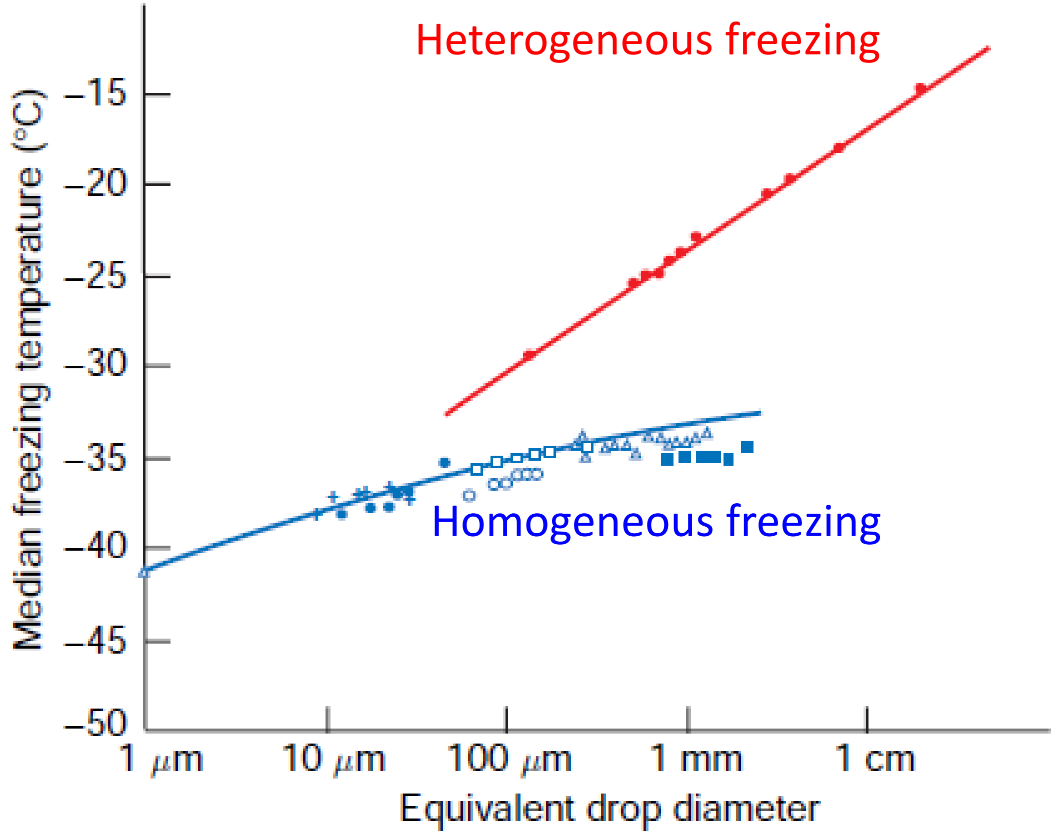
PRECIPITATION MECHANISMS
Cold Cloud Processes
Warm Cloud Processes
Homogeneous Freezing Nucleation
Aggregation
Vapor Deposition
Cold-rain Process
Bergeron Process
Secondary Ice
Riming
Heterogeneous Ice Nucleation
Cold Cloud
0 °C
Warm Cloud
Melting
Collision-coalescence
Continuous Collection
Breakup
Condensation
Warm-rain Process
CCN Activation
Updraft
Evaporation
H2O(v)
Particles CCN IN
Rainfall

Cold cloud

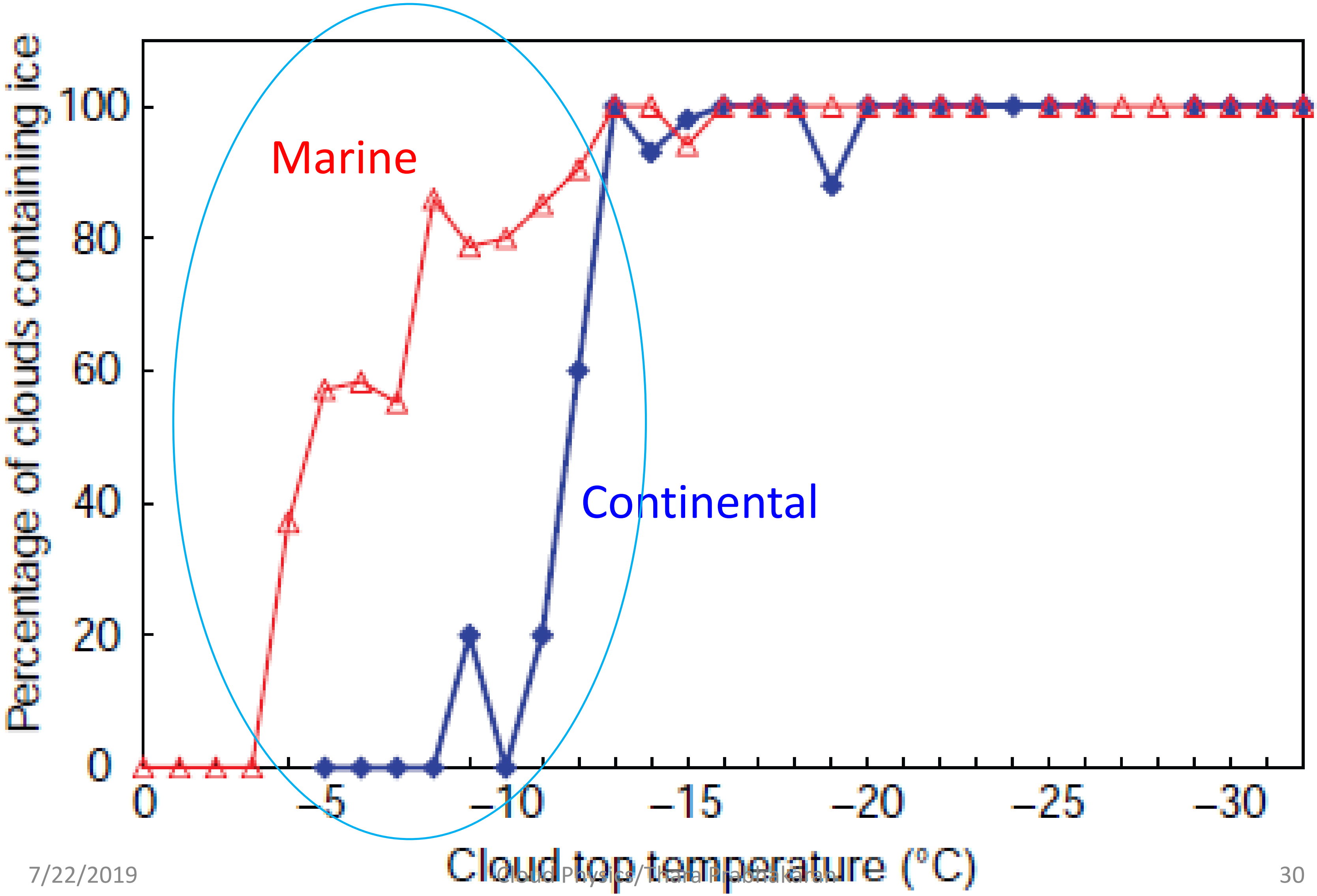
- Supercooled liquid, ice particles
- Mixed phase cloud
- Glaciated cloud

Homogeneous nucleation (occurs in T< -38oC)

Heterogeneous nucleation (warmer temperatures)



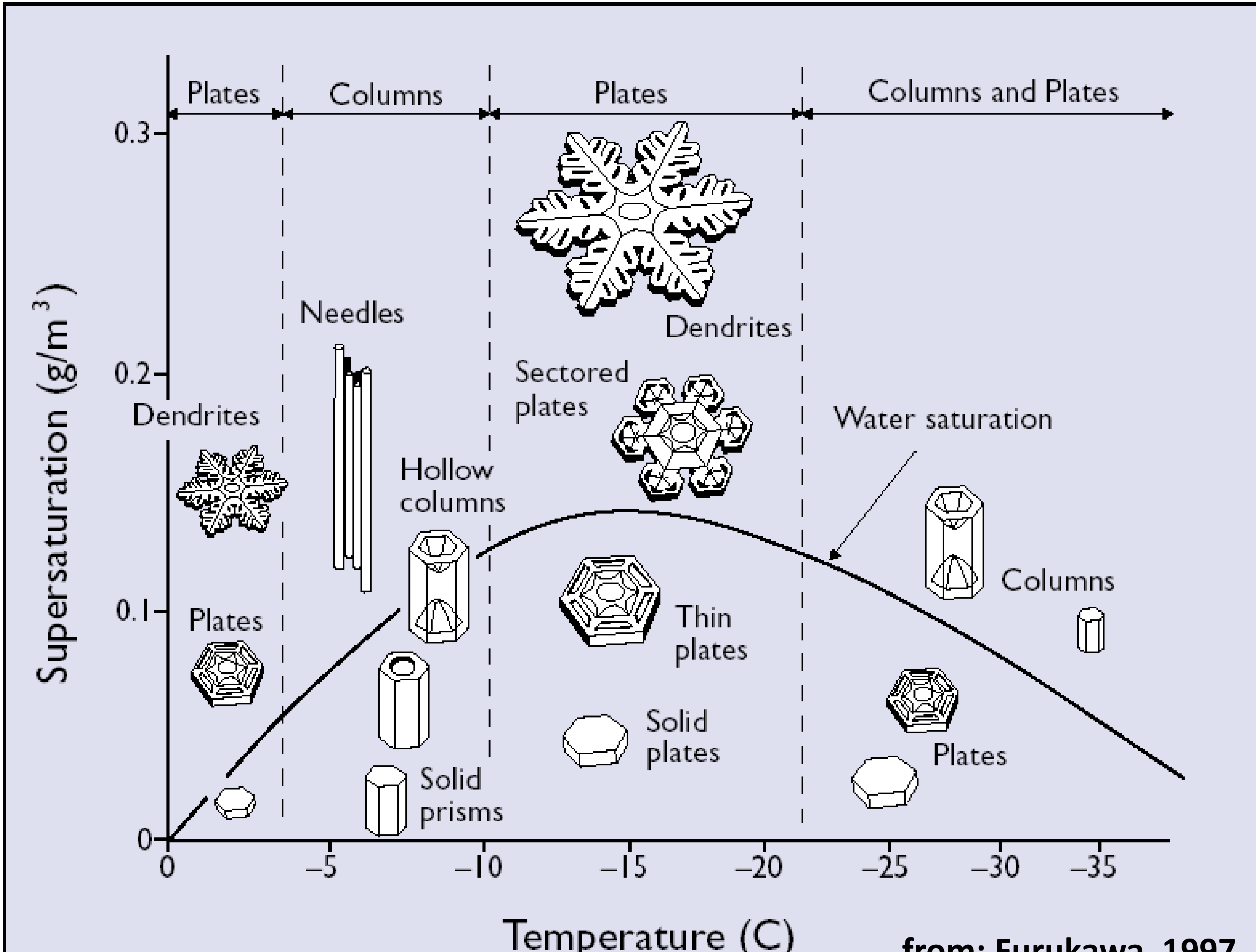
Percentage of clouds containing ice >1L-1 with Cloud Top Temperature



Supercooled liquid

- Cloud droplets or frozen rain/drizzle drops
- Hazardous for the aircraft flying in the mixed phase region
- Sometimes seen at higher altitudes under strong updrafts
- Contributes to riming: Deposition of super-cooled liquid droplets on frozen drops or ice crystals

Ice crystals: Habit Diagram



from: Furukawa, 1997

Definition of ice nucleating particles

- ***An ice nucleus is an aerosol particle which acts as the nucleus for the formation of an ice crystal in the atmosphere.***

requirements:

*** Insoluble in water**

*** size > 0.1 µm**

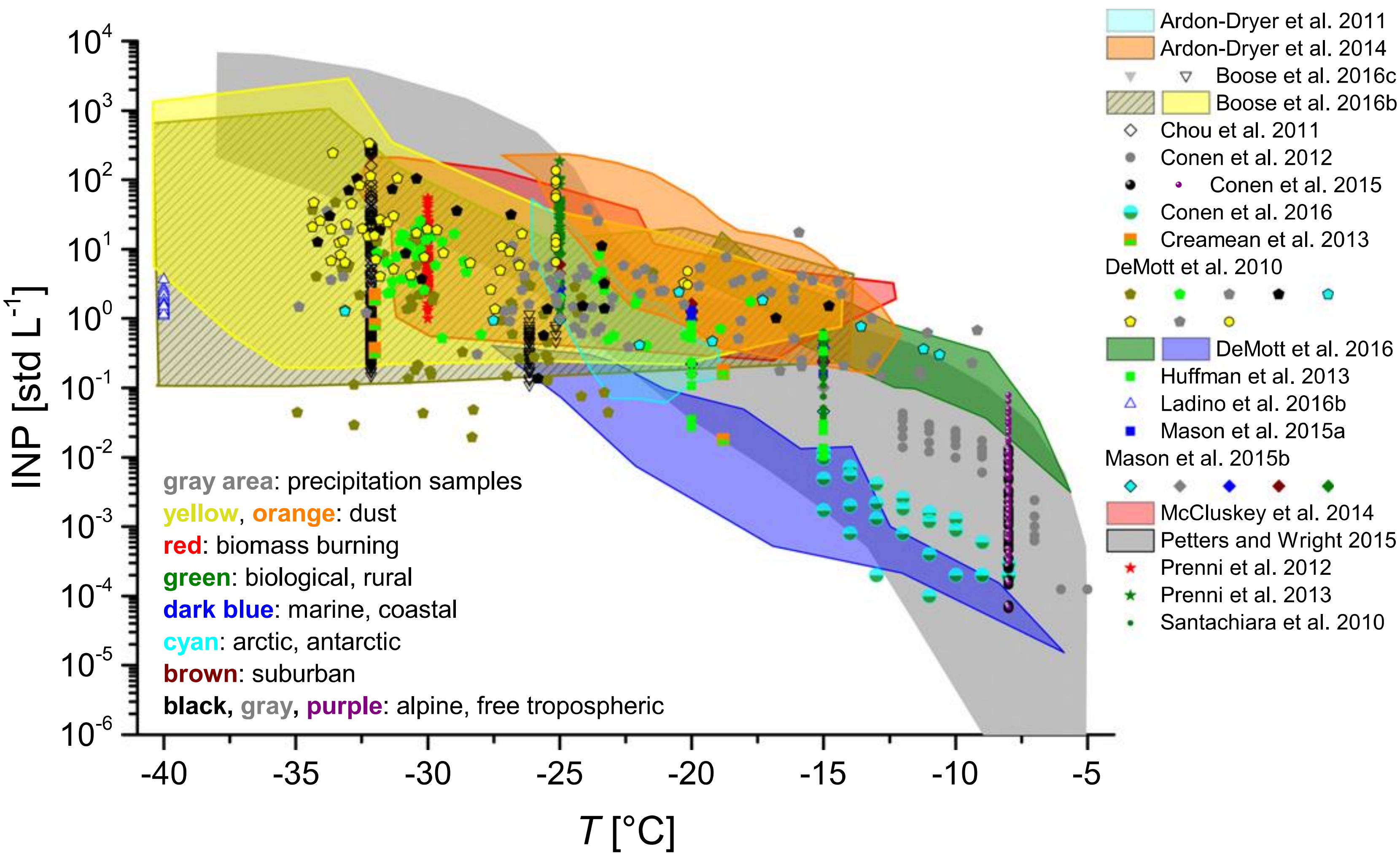
*** ice active sites on the surface**

*** crystallographic shape similar to ice (hexagonal)**

atmospheric concentrations of ice nuclei: < 10 per liter

well-known types of atmospheric ice nuclei: mineral dust, soot particles, biological particles (bacteria), Clay (also found), organic material –effective IN

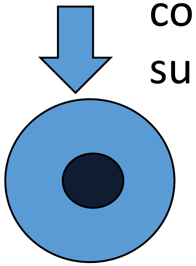
INP concentrations (Kanji et al. 2017)



ICE nucleation modes

Condensation freezing

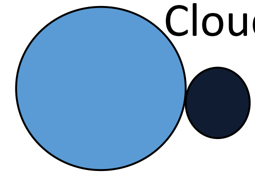
Water molecules collect on to the surface



Freezing nucleus (within the droplet)
(requires air supersaturated with respect to water)

Liquid water forms and then freezes

Contact freezing

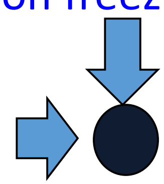


Cloud droplet

Particle (contact nucleus)

Note: Temperature at which a particle can act as ice nuclei depends on the mechanism of ice nucleation and the history of the particle (basic difference is whether nucleation is from the vapor/liquid phase)

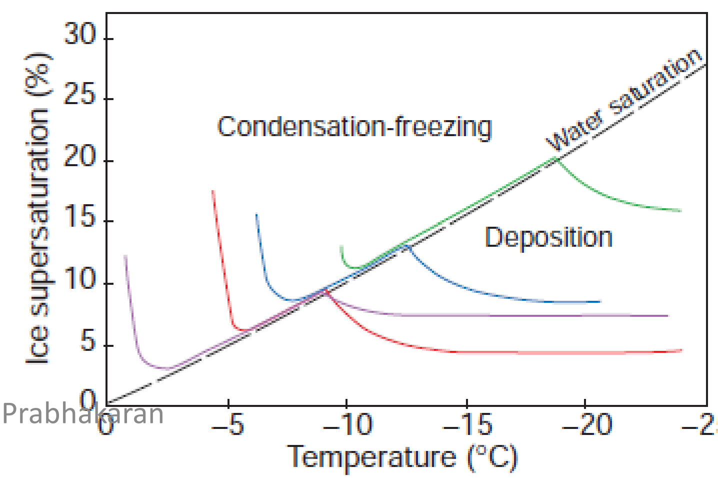
Deposition freezing



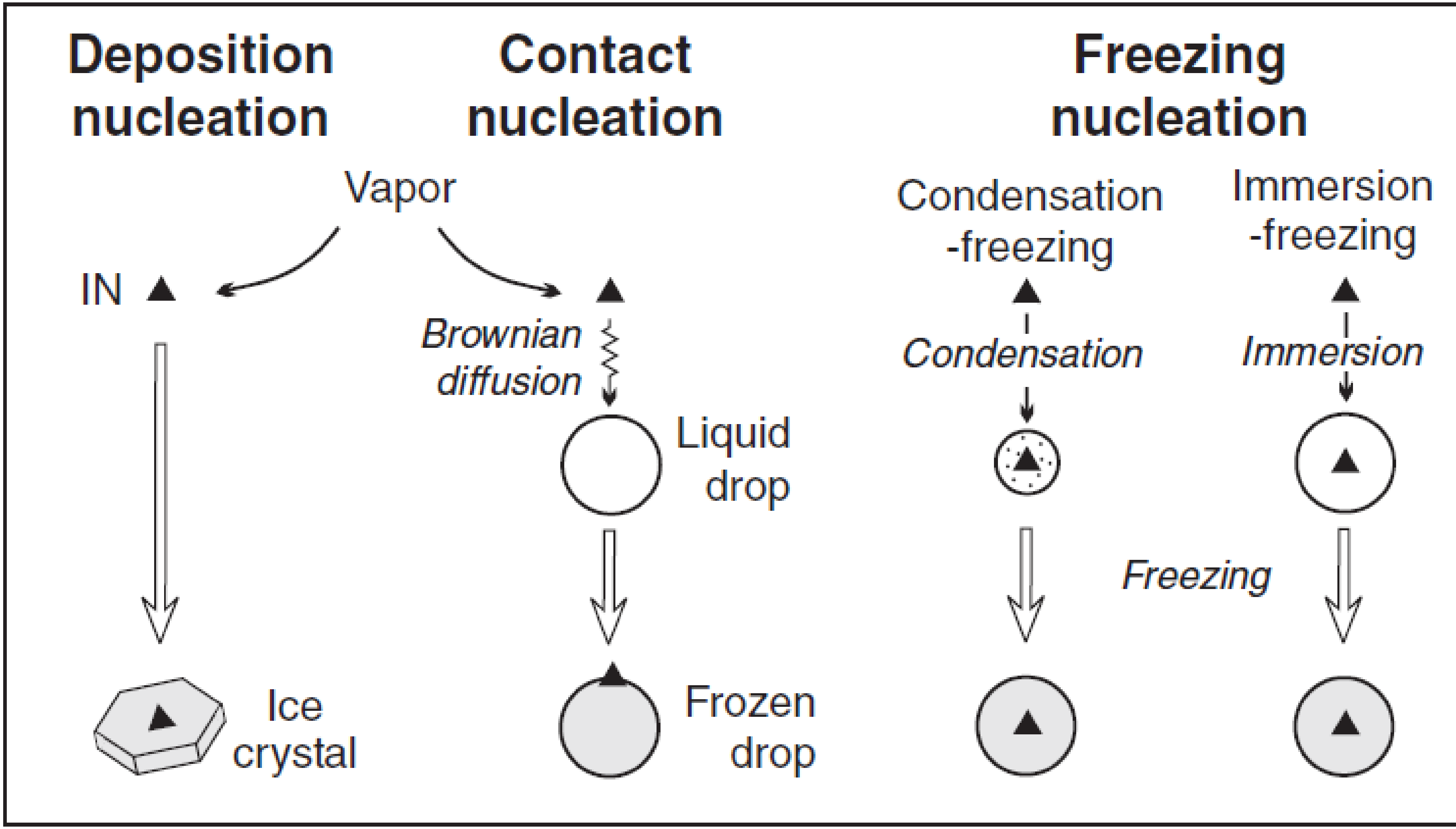
Deposition nuclei

Ice formation through **vapour deposition** (requires air supersaturated with respect to ice)

Onset of ice nucleation



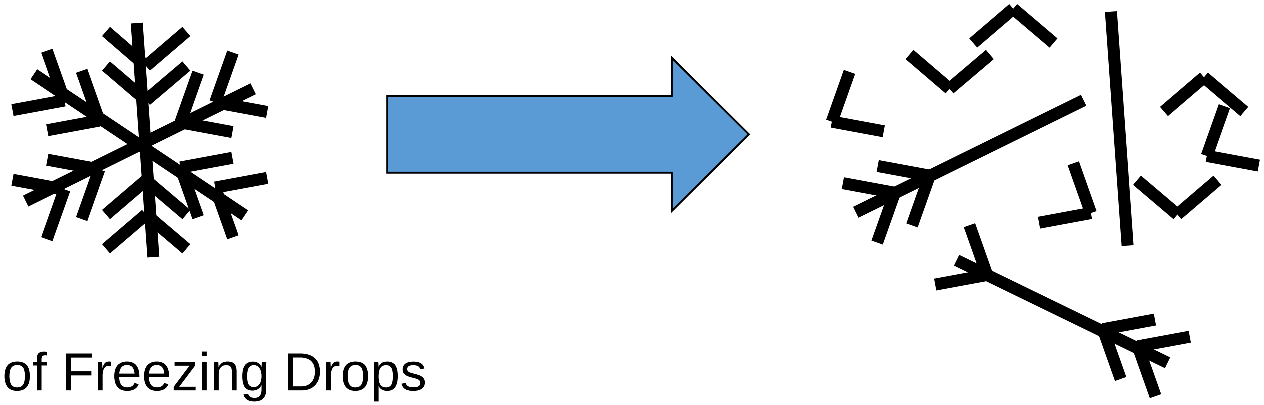
ICE nucleation modes



Ice nucleation and growth (-28oC)

Ice Multiplication Process

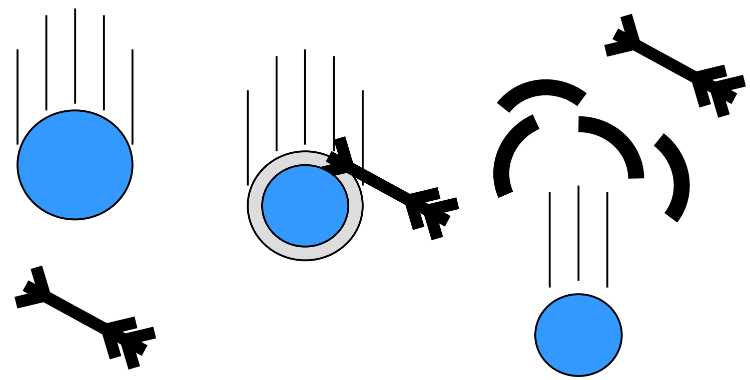
- Fracture of Ice Crystals



- Splintering of Freezing Drops

<u>During ice particle riming under very selective conditions:</u>

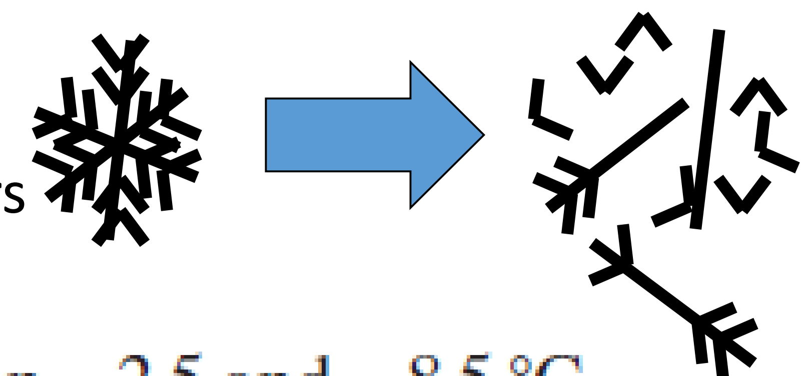
1. Temperature in the range of –3 ° to –8 °C.
2. A substantial concentration of large cloud droplets (D >25 μm).
3. Large droplets coexisting with small cloud droplets.



Sequence of events in the ice multiplication process

1. Freezing of Water drops
2. Supercooled droplet freezes (in isolation or after colliding with an ice particle)
3. Freezing of water drops on to ice particle lead to Riming
4. Mesh of ice shoots through the droplet and freezes enough water to raise temperature to zero degree C
5. Transfer of heat from partially frozen droplet to cold ambient air – ice shell forms over droplets and thicken inward
6. Water is trapped inside – as it freezes, expands, increase stress on ice shell – which explodes

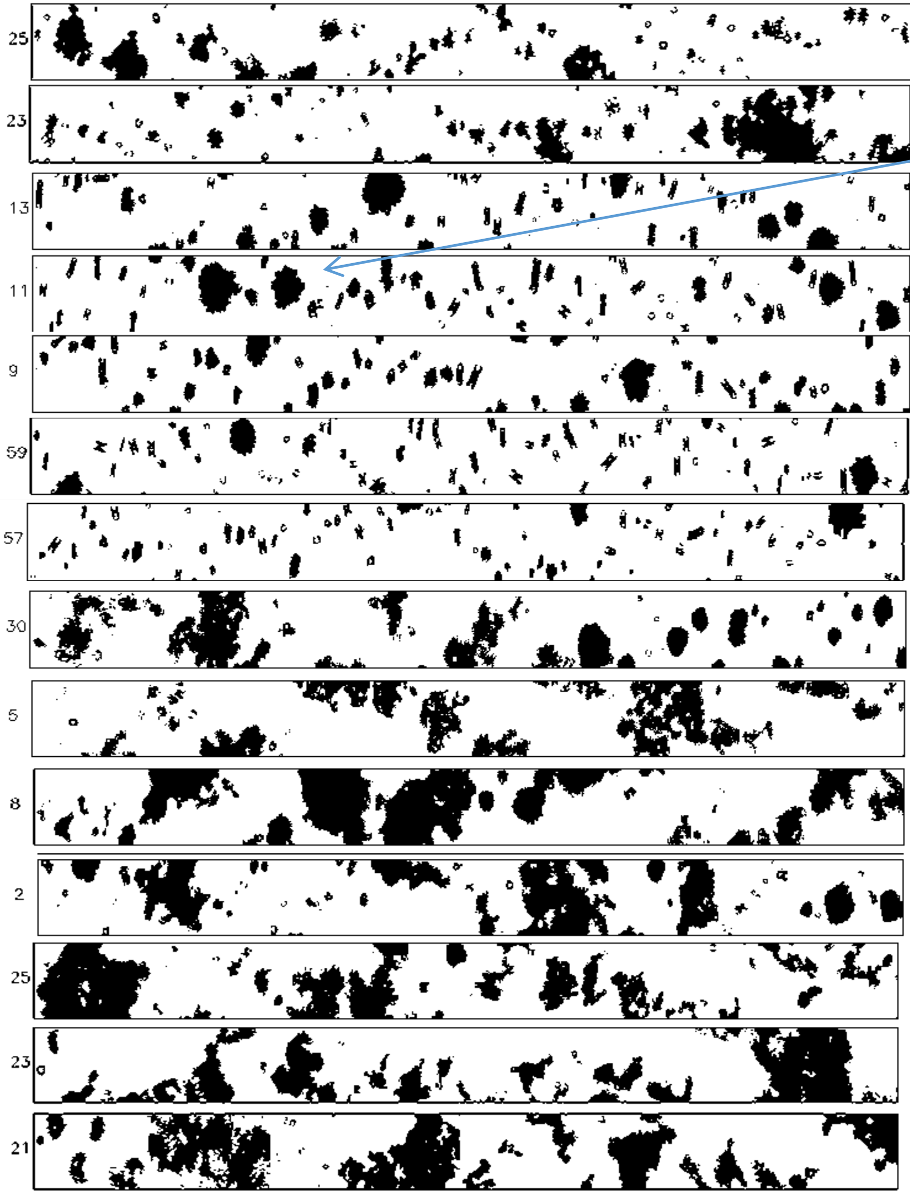
7. Results in numerous small ice splinters



$\geq 25\ \mu m$, temperatures are between -2.5 and -8.5 °C

Clear evidence of snow leading to precipitation formation

Width of strip=1600 µm



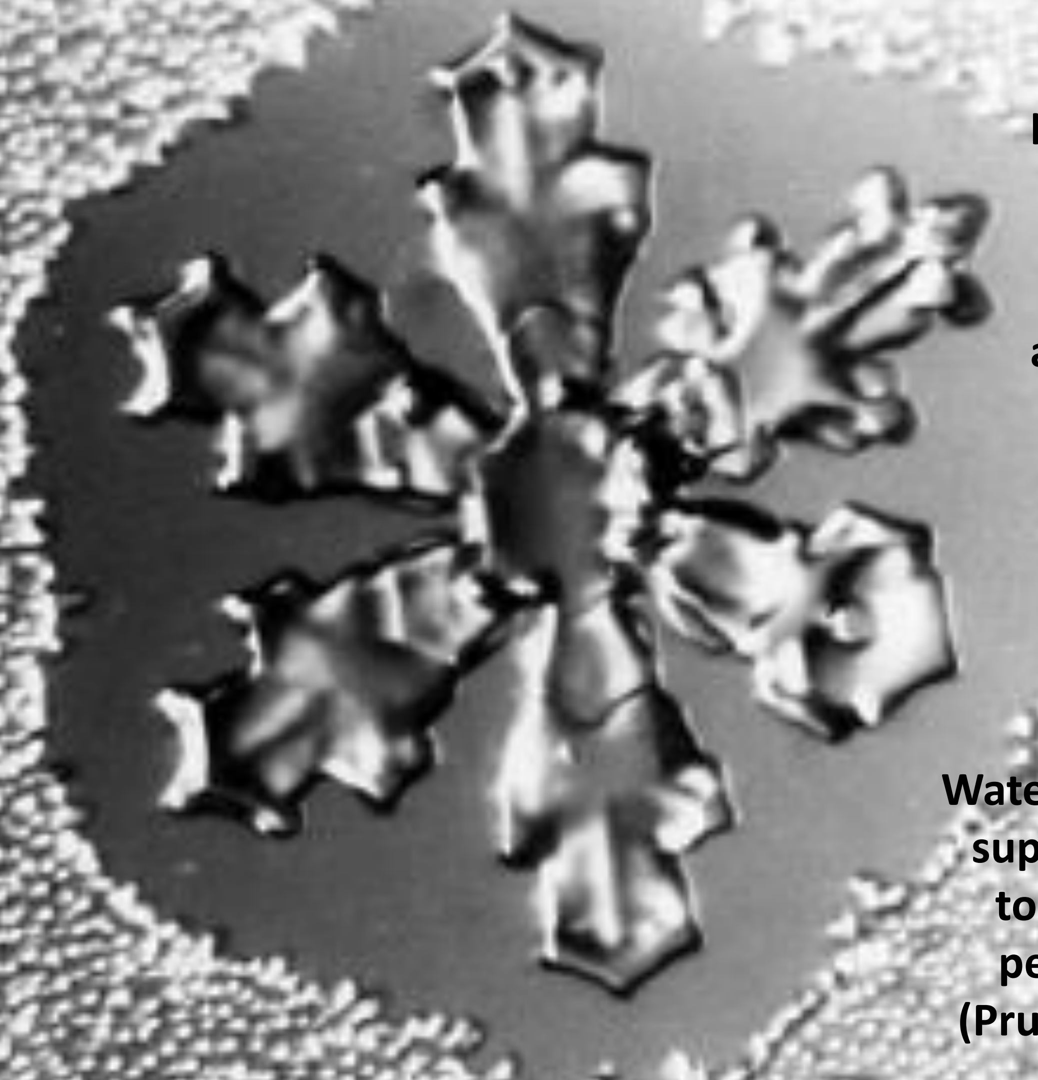
Time (UTC)	Temp (°C)
095025	-8.59
095023	-8.60
094713	-7.22
094711	-7.11
094709	-7.16
094659	-6.59
094657	-6.59
094430	-4.49
094305	-4.58
094208	-3.38
094202	-3.67
094125	-2.54
094123	-2.49
094121	-2.74

Needles and Graupel drops

Active Hallet Mossop Zone

Ice multiplication

Sachin Patade et al., 2015, Atmospheric research



The equilibrium vapor pressure of water vapor with respect to ice is less than that with respect to liquid water at the same subfreezing temperature

Water-saturated cloud will be supersaturated with respect to ice at a rate of about 1% per degree of supercooling (Pruppacher and Klett 2010).

Bergeron Findeisen process

- **Ice particles in clouds with supercooled water grow rapidly to precipitation-sized particles.**
- **Supercooled droplets evaporate and ice particles grow at the expense of vapour through depositional growth**

Growth of ice particles accretion

2. Riming

Riming is a mode of accretion growth of ice particles.

- **Super-cooled liquid** stick to and freeze on the surface of the ice particles to become **rime** - a rimed crystal
- Original Ice particle is completely masked by the rimes, it becomes a **graupel**.
- When a graupel grows larger than 5mm in size, it is called **hail**.

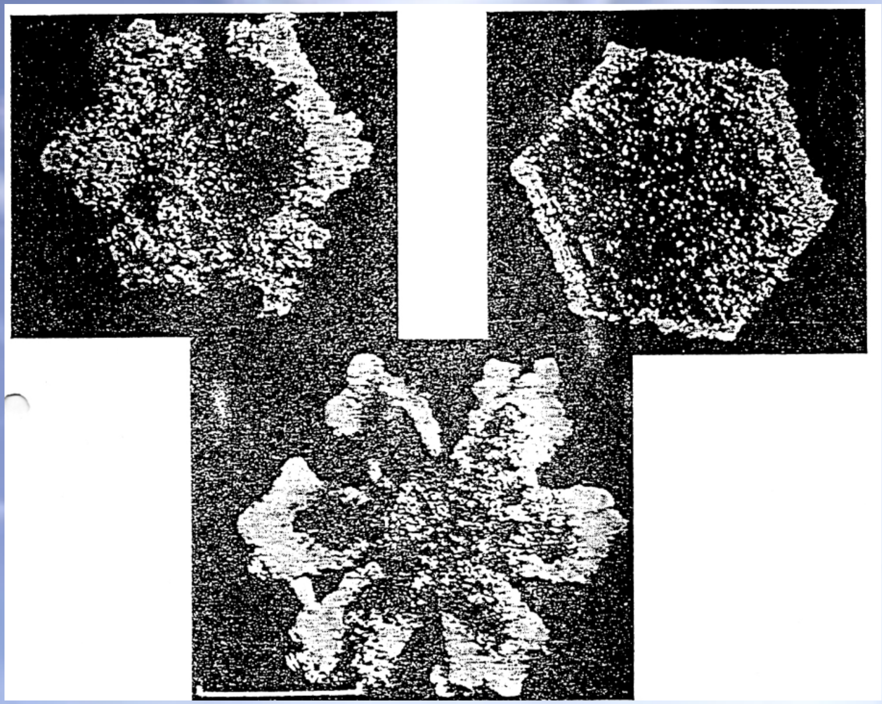
Deposition of super-cooled liquid droplets on frozen drops or ice crystals

→ collision process

→ dependant on collision partners

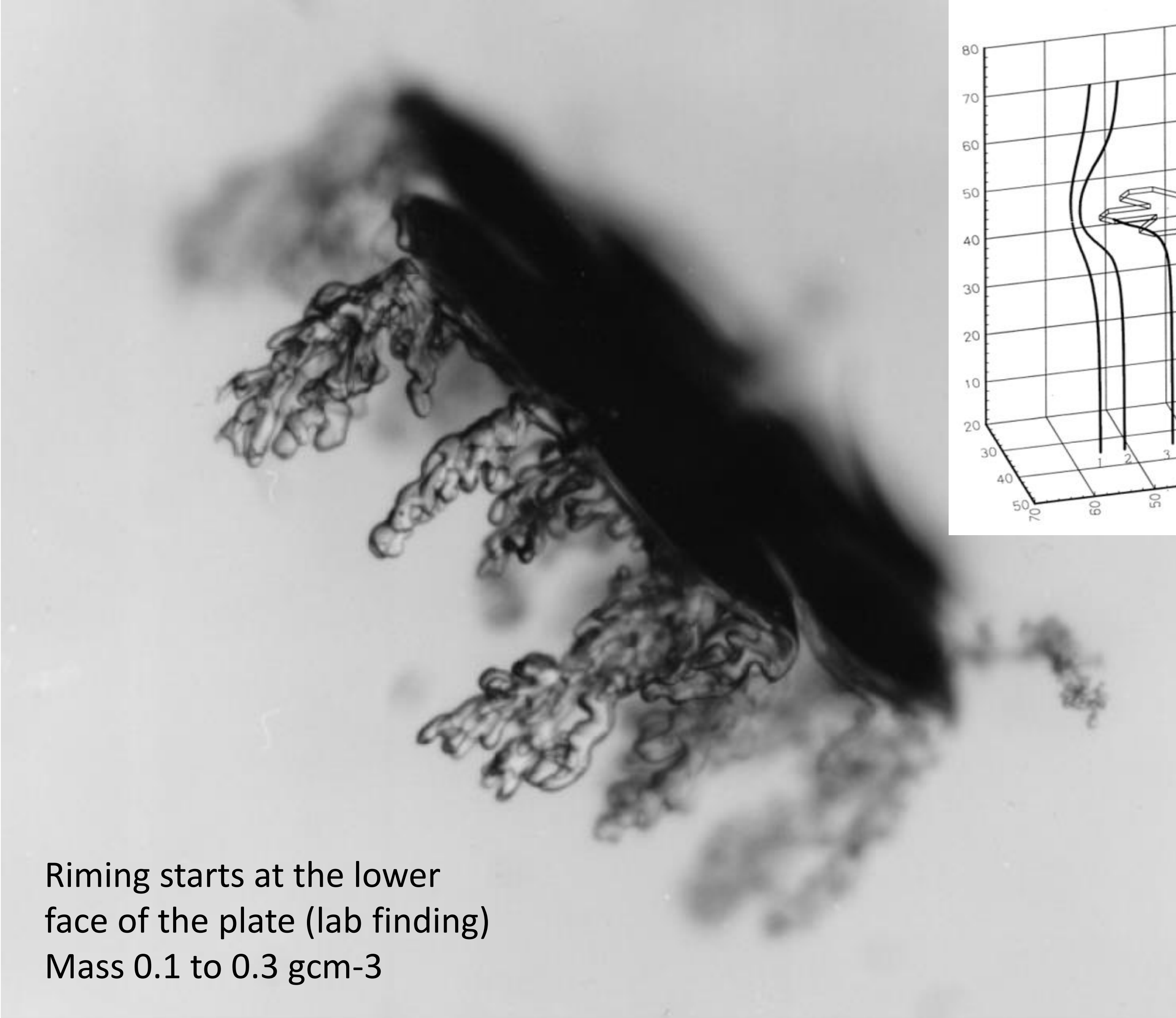
Growth of ice particles

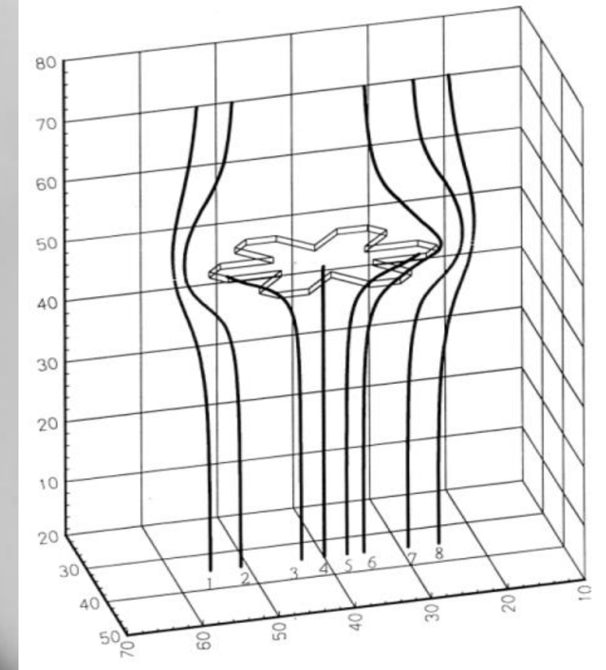
2. Riming



Rimed planar ice crystals of 2 to 3 mm diameter, rimed column ice crystal of 1.5 mm length

from: Pruppacher and Klett, 1997

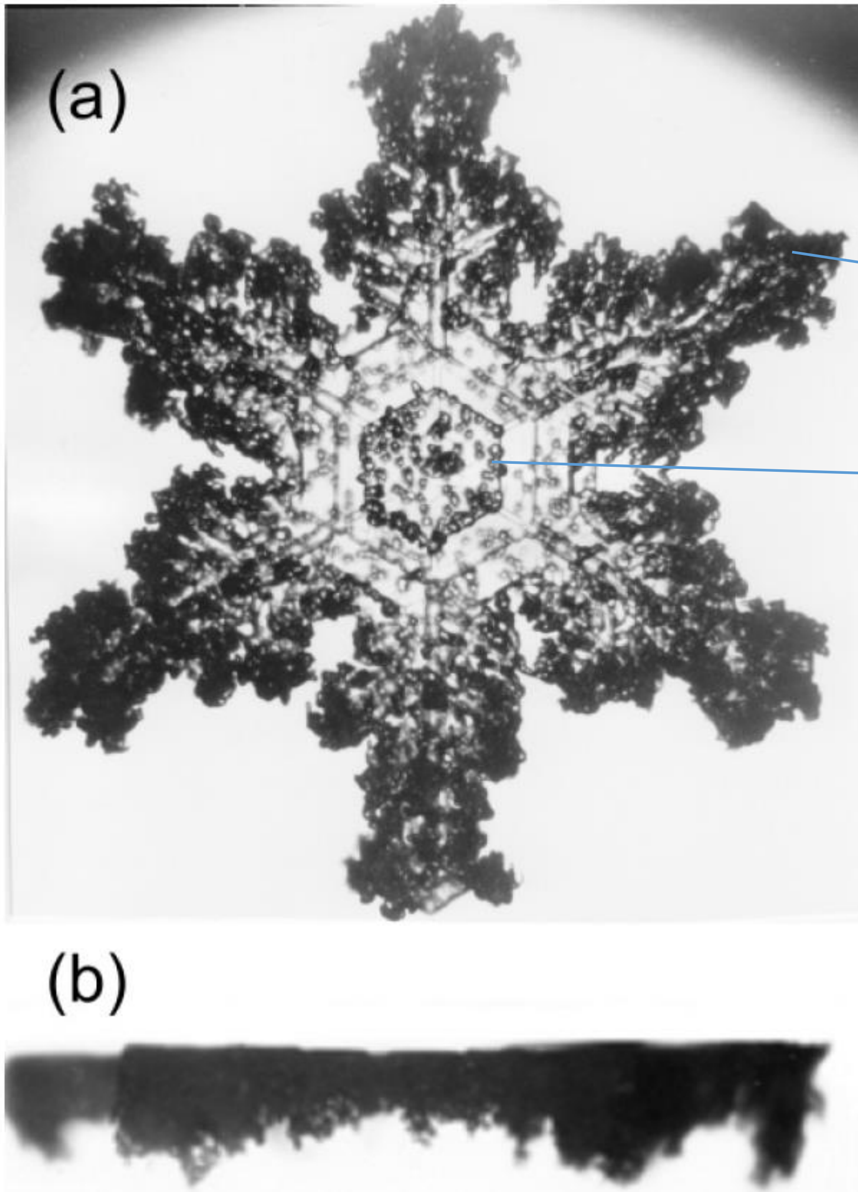




Riming starts at the lower
face of the plate (lab finding)
Mass 0.1 to 0.3 gcm-3

10.9 A rimed sector plate. The rime grows just on one side, presumably the rside during the fall of the plate. Photo courtesy of Dr Charles A. Knight.

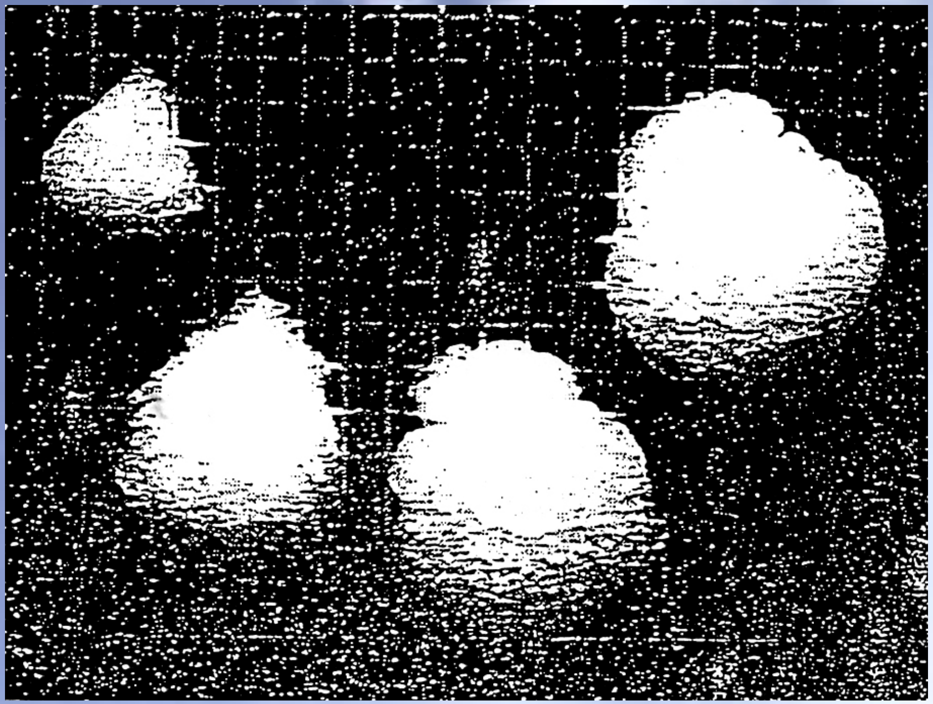
Rimed Dendrite with a central hexagonal plate



Iwai (1983)

Growth of ice particles

2. Riming



conical and lump graupel

from: Pruppacher and Klett, 1997

growth of graupel

1. **deposition of super-cooled droplets mainly at the lower side**
   → conical graupel
2. **balance point changing → tumbling**
   → lump graupel

laboratory experimental studies

graupel density, from 0.05 to 0.9 g cm^{-3}

Continued riming of ice crystals would eventually lead to the formation of graupel.

Growth of drop into a conical shaped graupel

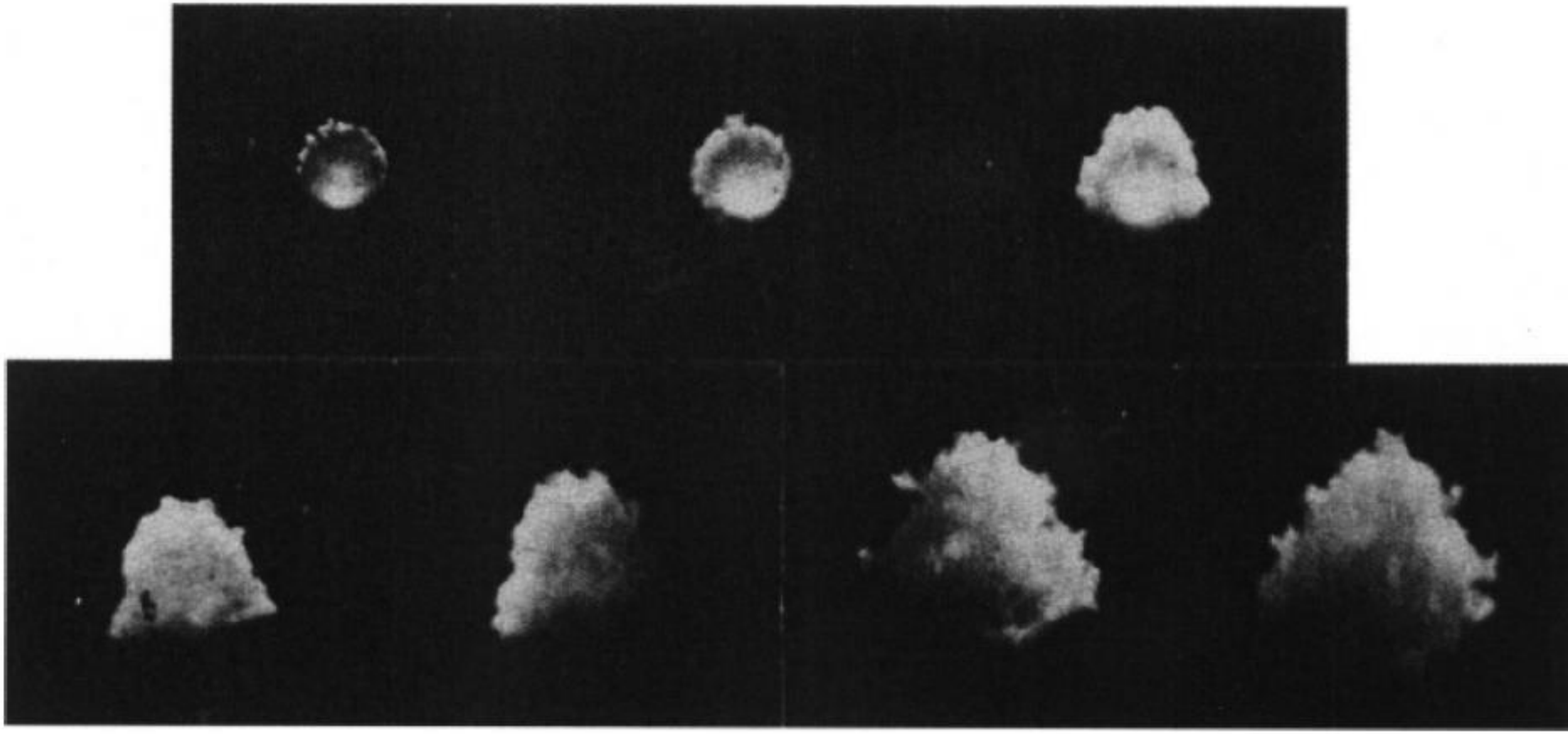


Fig. 10.10 The growth evolution from a drop into a conical graupel. The diameter of the frozen drop is about 450 μm; the diameter of the graupel at the last stage of development is about 2 mm. From Pflaum *et al*. (1978). Reproduced by permission of the Royal Meteorological Society (UK).

Collection kernels of graupel (6, 10 and 15 microns)

$$K_{\mathrm{ice6}} = 10.06(mv)^{0.847},$$

$$K_{\mathrm{ice10}} = 10.22(mv)^{0.738},$$

$$K_{\mathrm{ice15}} = 10.72(mv)^{0.728},$$

Blohn *et al.* (2009)

M v is momentum of graupel of mass m and fall velocity v

Ice –ice collisions

Graupel collecting ice crystals

- -Ice particle collide – they can stick together (sintering- fusing the surfaces),
- -interlock due to the branches of ice crystals such as dendrites
- -bounce apart

- Ice particle can collide to form large ice particles, such as snow flakes

Ice accretion growth

Occur in the dry growth or wet growth regime.

Dry growth : supercooled drops collide with an ice particle and freeze on it. (freezing of water also releases latent heat, which will warm the ice particle surface to a temperature above the environmental air. heat can be dissipated efficiently so that the **crystal surface temperature remains colder than 0°C**.)

Wet growth regime : if the collection of supercooled water droplets is going on rapidly enough such that the accumulated heat cannot be dissipated quickly, the ice surface may approach 0°C and the above spontaneous freezing may or may not occur. **This occurs where the liquid water content of the supercooled droplets is high**. The amount of ice formed depends on how fast the heat is dissipated, and not all the water droplets accreted turn into ice.

Hailstones

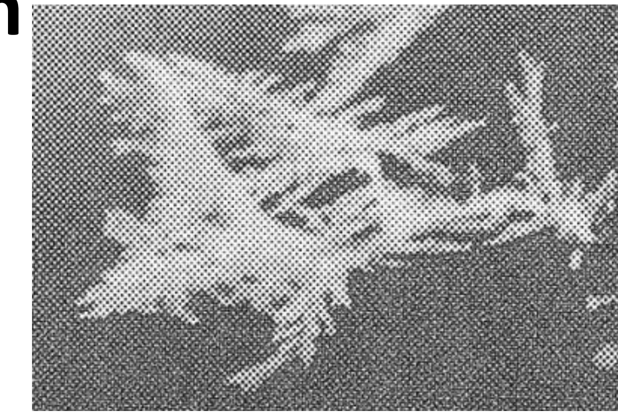
Hailstones represent an extreme case of the growth of ice particles by riming. They form in vigorous convective clouds that have high liquid water contents.

The largest hailstone reported in the USA (Nebraska) was **13.8 cm in diameter** and weighed about 0.7 kg. However, hailstones about 1 cm in diameter are much more common.

If a thin section is cut from a hailstone and viewed in transmitted light, it is often seen to consist of alternate dark and light layers (Figure follows).

The dark layers are opaque ice containing numerous small air bubbles, and the light layers are clear ice. Clear ice is more likely to form when the hailstone is growing wet.

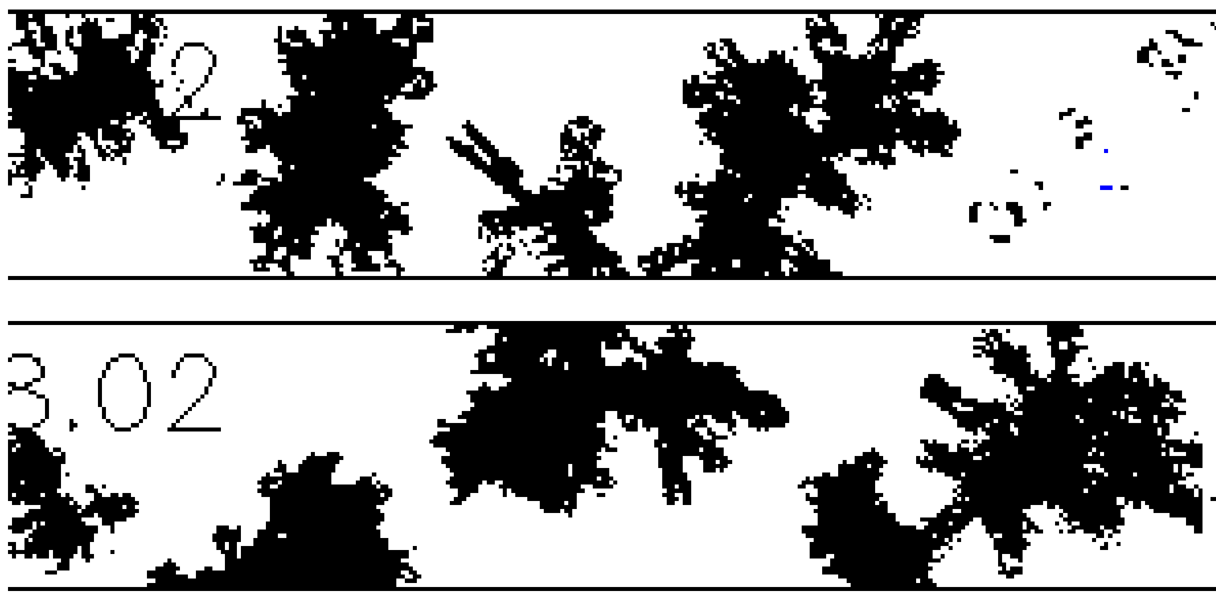
Growth by aggregation



- **Ice particles grow by colliding and aggregating**

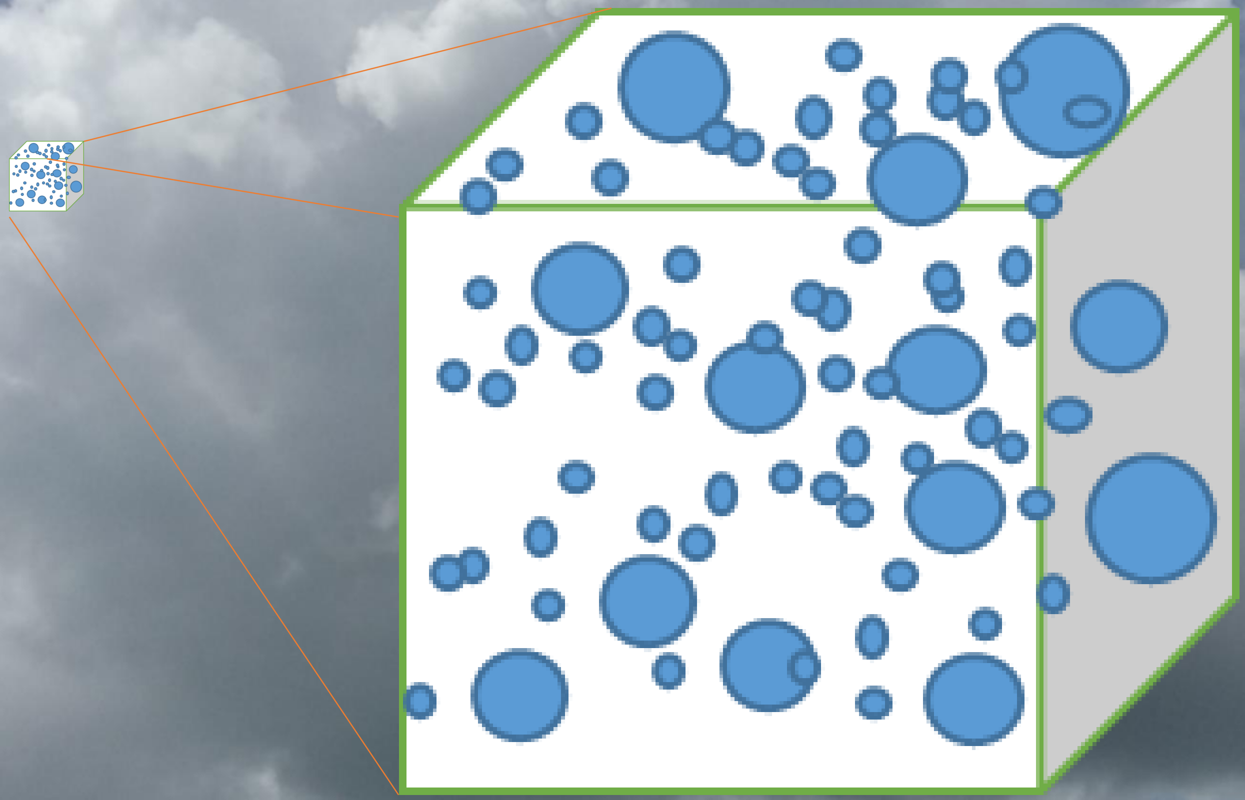
- **Collision depends on their terminal fall speeds**

- **Frequency of collisions are also enhanced if riming has taken place**

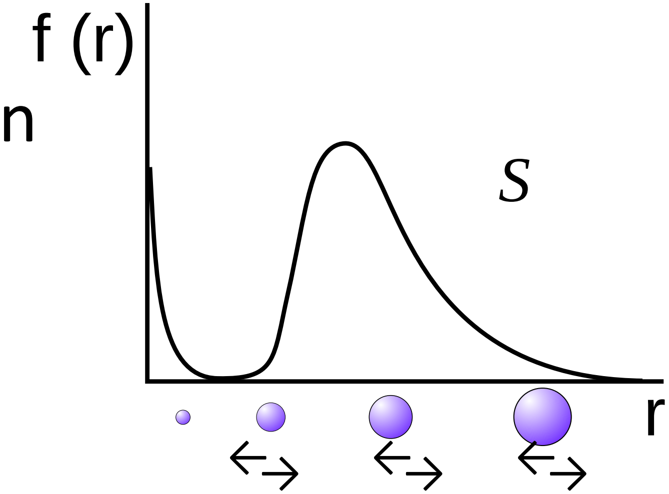


Aggregates of dendrites observed during CAIPEEX

How can we look at properties of clouds ? We consider cloud droplets in a cubic centimeter of cloud



Cloud particle size distribution

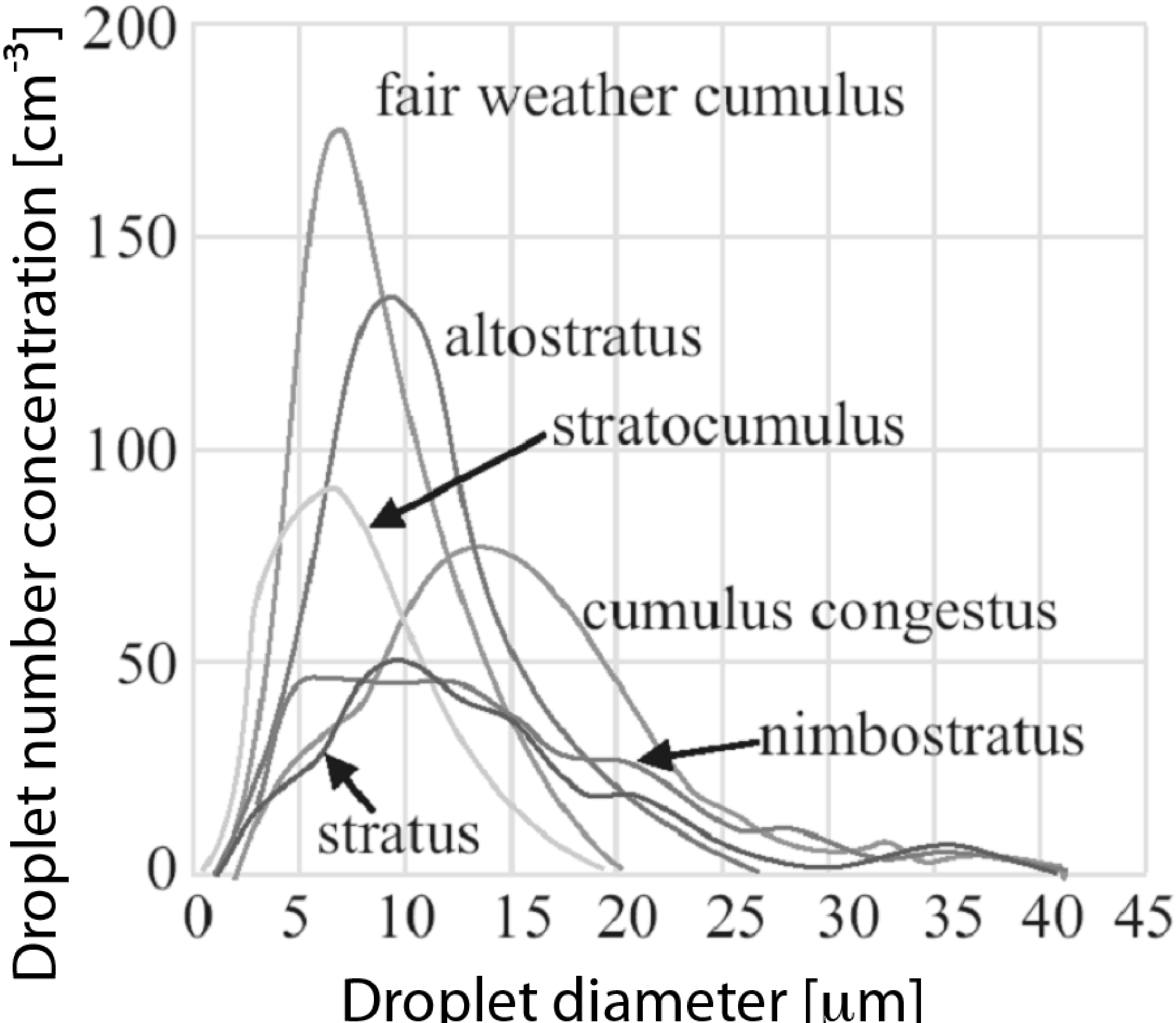


$$N = \int f(r)dr$$ number concentration (0 moment)

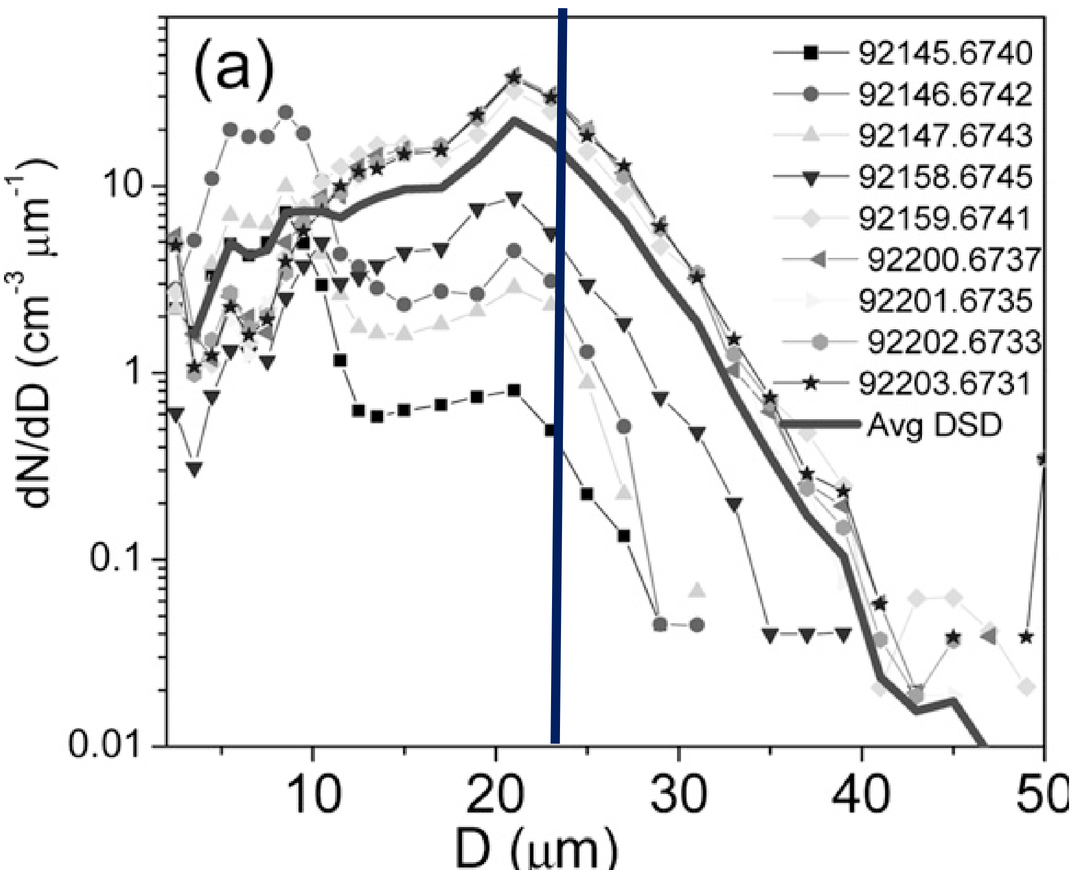
$$N\,\bar{r} = \int f(r)r\,dr$$ Integral radius of drops (1^{st} moment)

$$\beta \sim N\,\bar{r}^2 = \int f(r)r^2 dr$$ extinction coefficient (2^{nd} moment)

$$W \sim N\,\bar{r}^3 = \int f(r)r^3 dr$$ water content (3^{rd} moment)

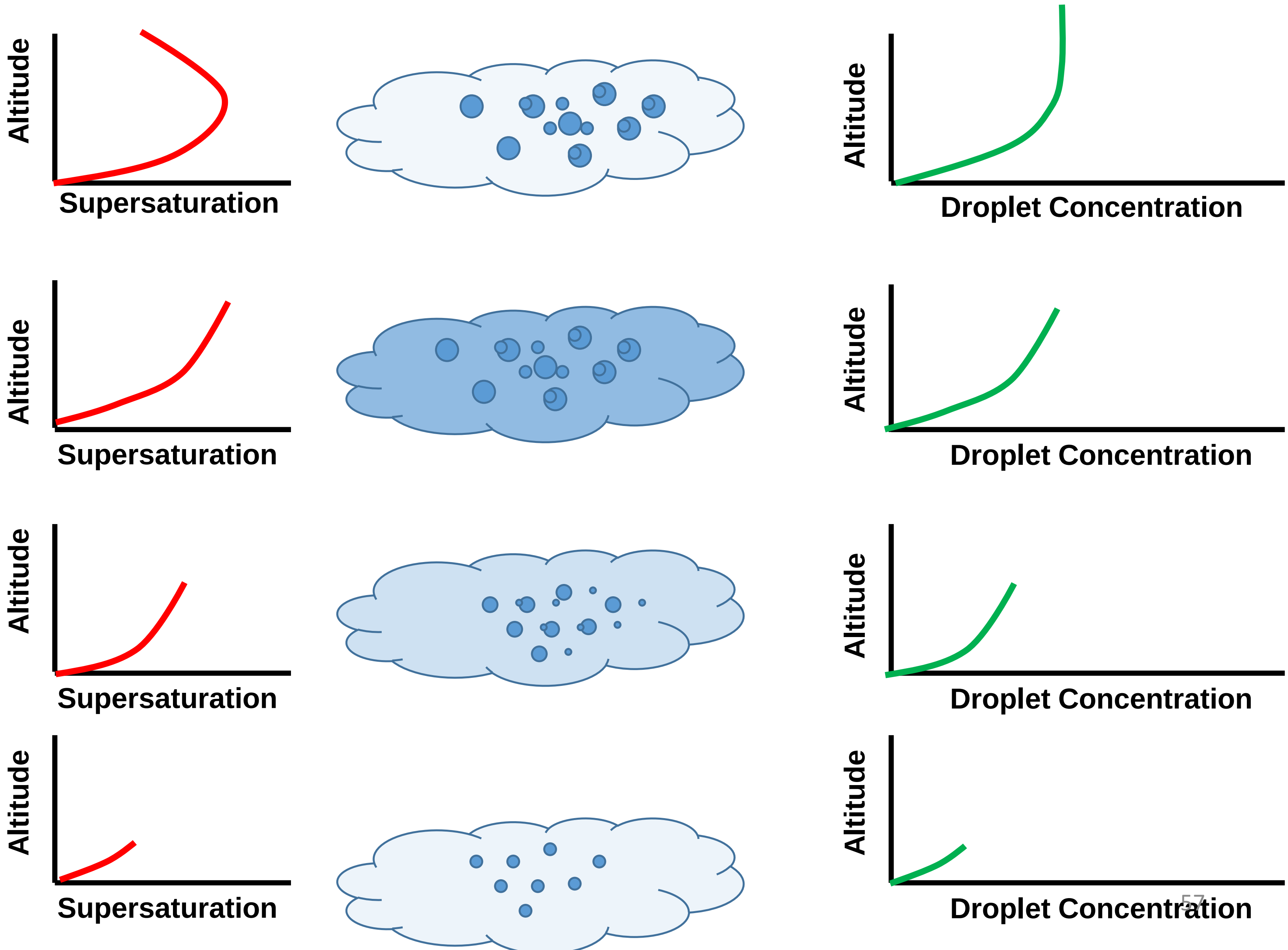

fair weather cumulus
altostratus
stratocumulus
cumulus congestus
nimbostratus
stratus
200
150
100
50
0
0
5
10
15
20
25
30
35
40
45
Droplet number concentration [cm^{-3}]
Droplet diameter [μm]

Rates of microphysical processes are determined by "local" DSDs, that display a significant variation



DSD: Drop size distribution

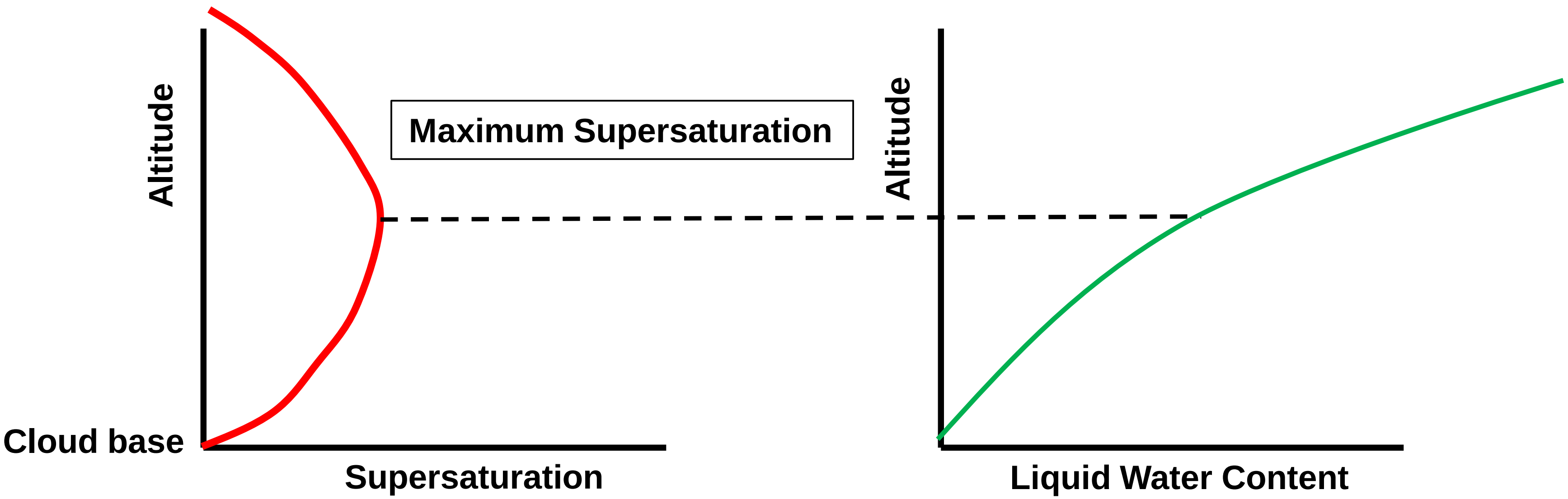
Air mass continues to ascend and cool, SS decreases as water vapor is depleted by condensational growth, no more new particles activated.



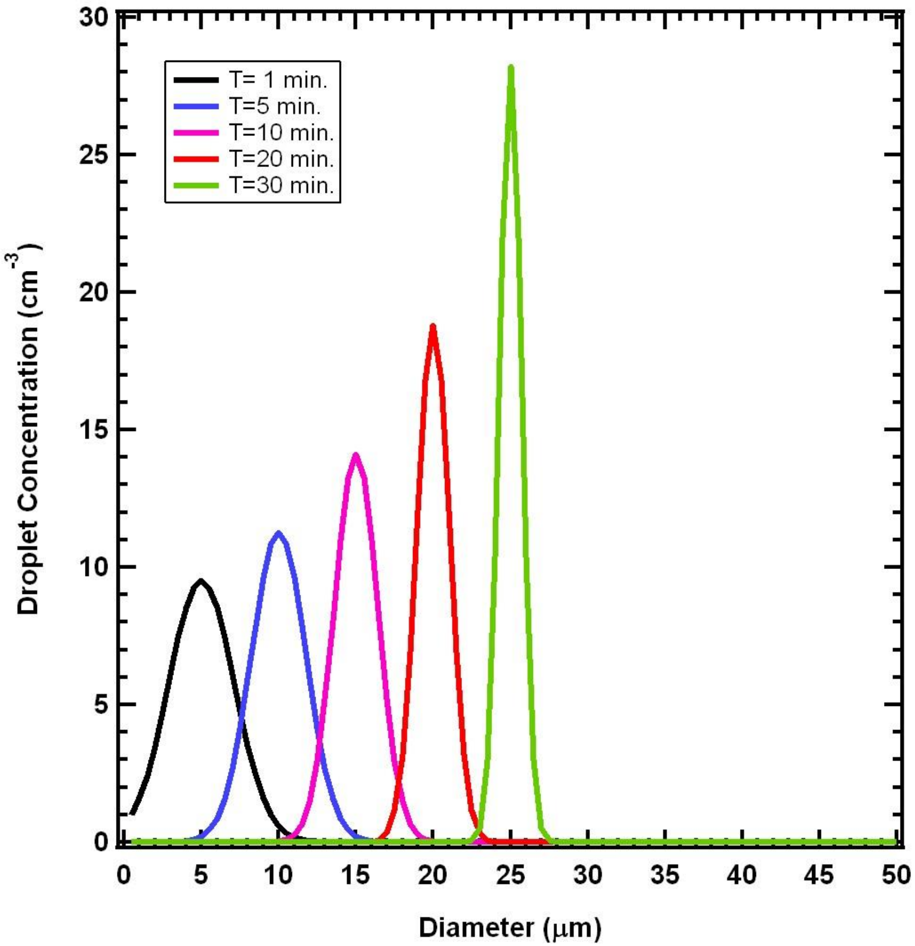
Total Mass (Liquid Water) Concentration (LWC)

- **In warm clouds, at any level above cloud base, a measurement of LWC tells us how much liquid water has condensed as the air mass rises**

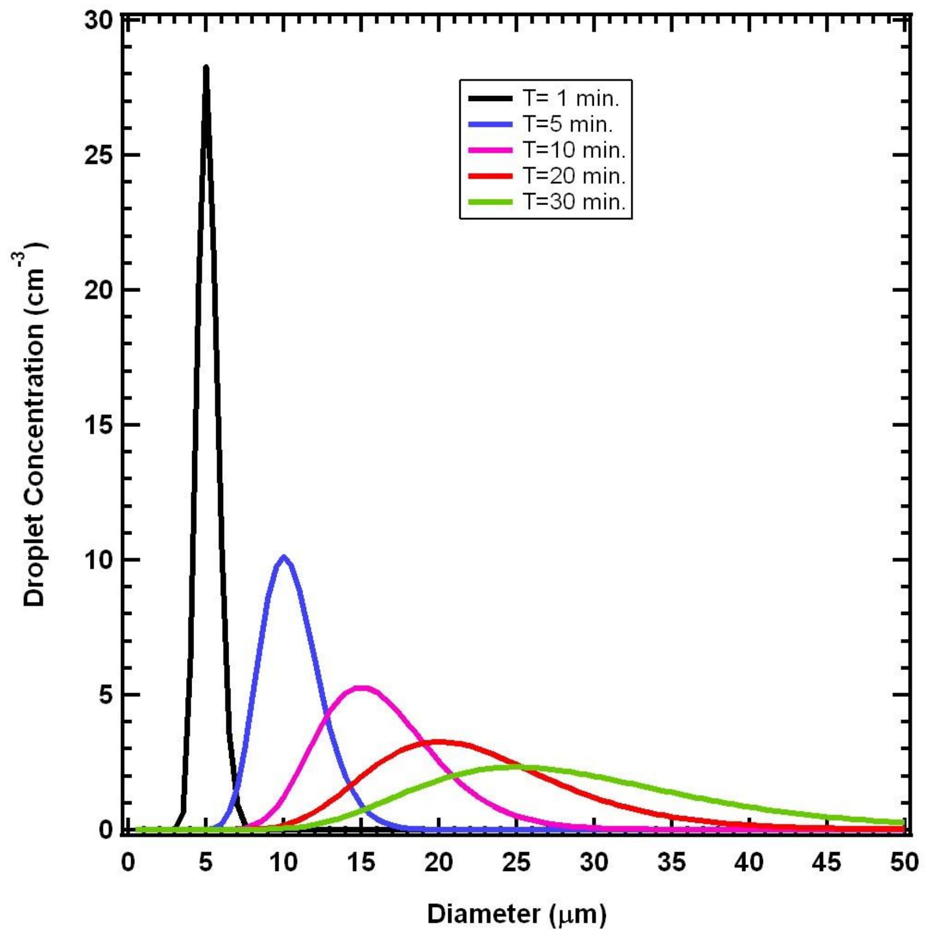
- **This can be compared with the calculated adiabatic liquid water content that predicts the maximum possible liquid water that can be removed from an ascending cloud mass.**



Simple Condensational Growth Model

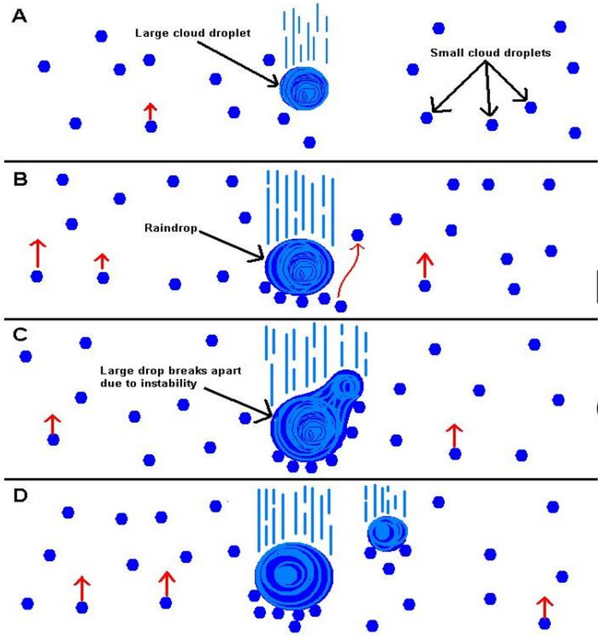


Observations



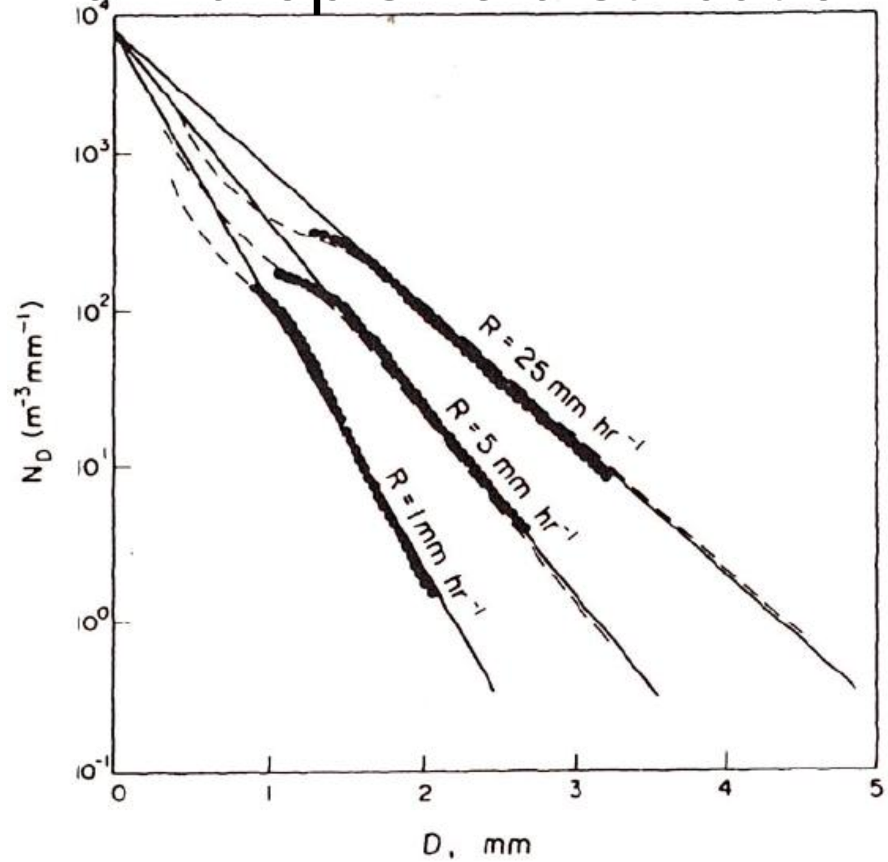
Condensational Growth rate ~ $1/D^2$

Rain drop size distribution



Raindrop forms

Falling large cloud drop collide and coalesce



$$N(D) = N_o \exp(-\Lambda D)$$

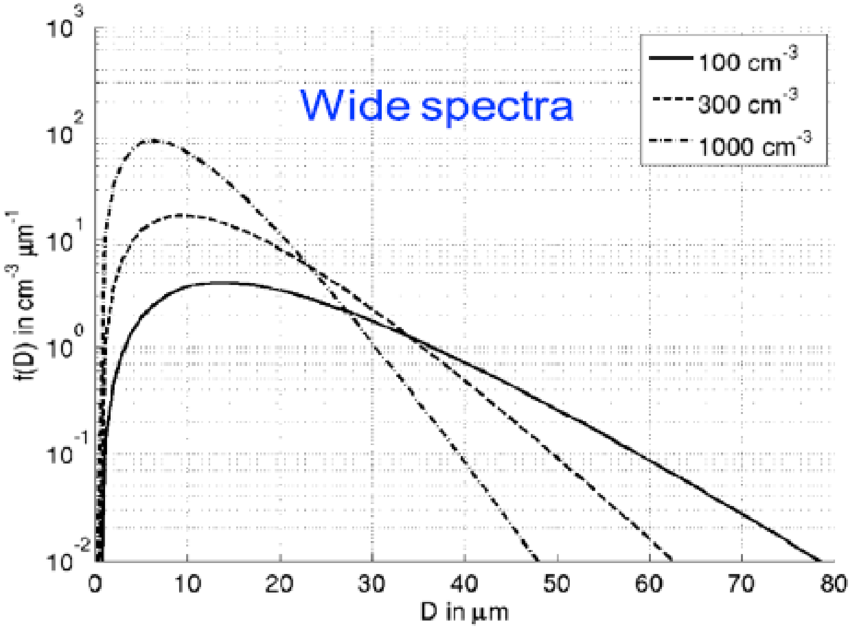
where $N(D)dD$ is the number of drops per unit volume with diameters between D and $D + dD$ and N_o and Λ are empirical fitting parameters. The value of N_o tends to be constant, but Λ varies with the rainfall rate.

Not true

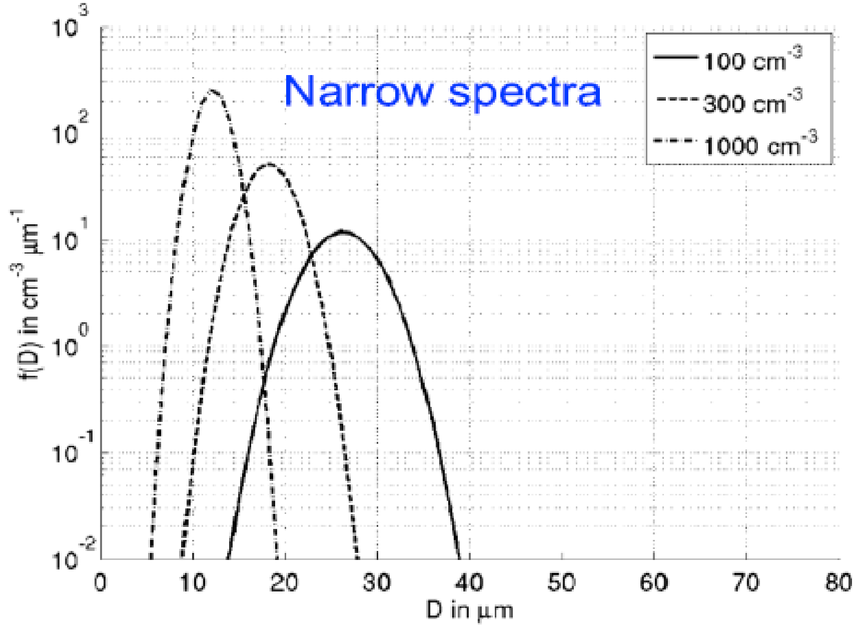
Bulk microphysical model uses ‘N^0’ and ‘Lamda’

4 parameters formula :
(gamma distribution)

$$f(m) = N_0 m^{\nu} e^{-\lambda m^{\mu}}$$



ν=1, μ=1/3



ν=6, μ=1

$$N = N_{0\Gamma} D^{\mu} e^{-\lambda_{\Gamma} D}$$

$$N = N_0 e^{-\lambda D};\ \mu = 0$$

intercept ($N_{0\Gamma}$), slope (λ_{Γ}), dispersion (μ)

Rain rate

Fall velocity of hydrometeors

$$R = \frac{\pi}{6} \int_o^{\infty} N(D_h) D_h^3 v_h(D_h) dD_h$$

Number size distribution of hydrometeors

Volume flux of precipitation through a horizontal surface (m3 m-2 s-1)

mm hr-1

Reflectivity

Measured backscattered intensity from the radar signal

$$Z = \sum_V D_h^6 = \int_o^\infty N(D_h) D_h^6 dD_h$$

$$\mathrm{mm}^6\ \mathrm{m}^{-3}$$

$$\mathrm{dBZ} = Z\ [\mathrm{dB}] = 10 \log \left(\frac{Z}{mm^6 m^{-3}} \right)$$

$$Z = 300 R^{1.5}$$

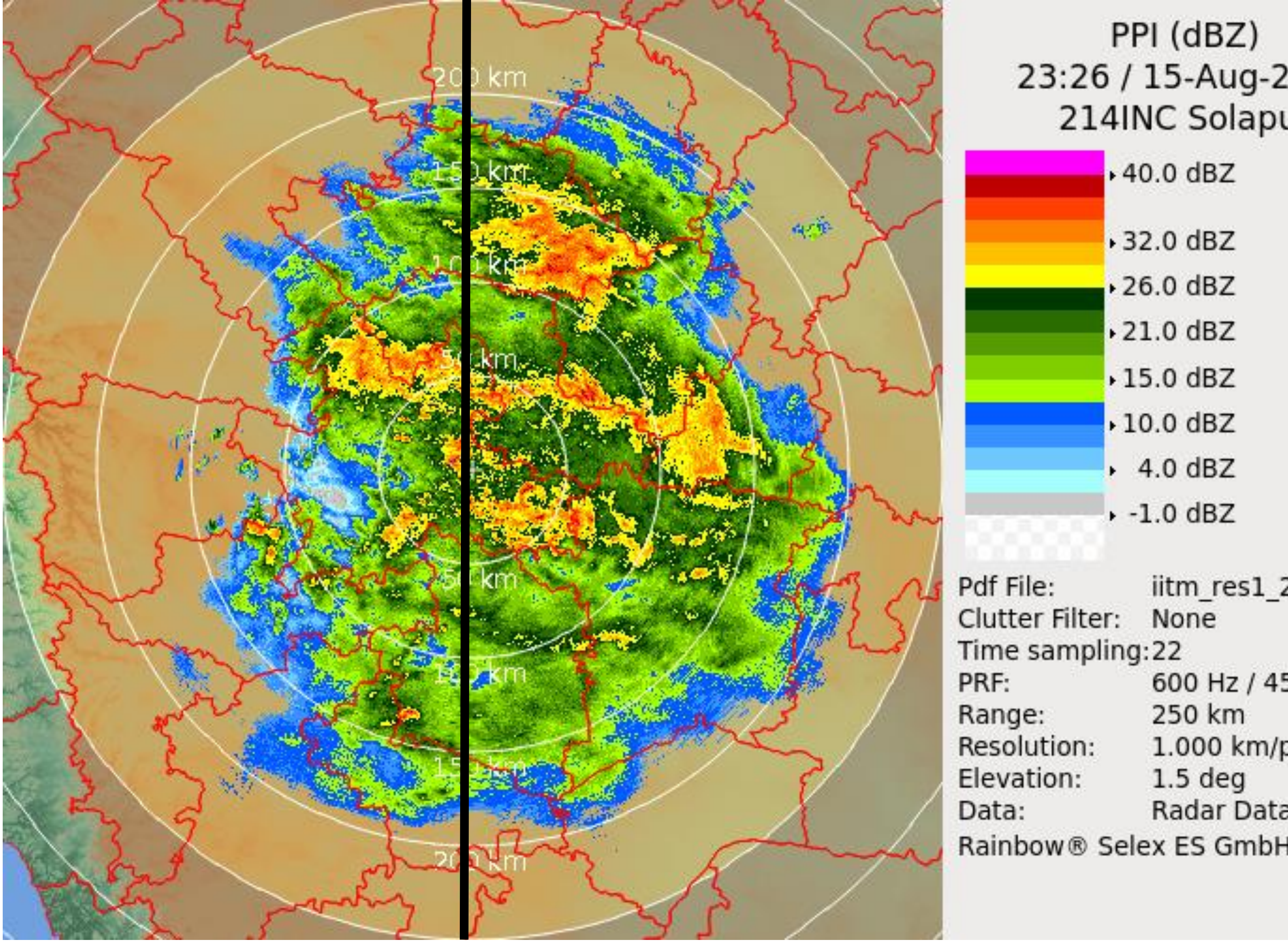
R (mm h^{-1})	0.1	1	10	100
Z ($mm^6\ m^{-3}$)	9.5	300	9500	300000
dBZ	10	25	40	55

Terminal velocities of hydrometeors

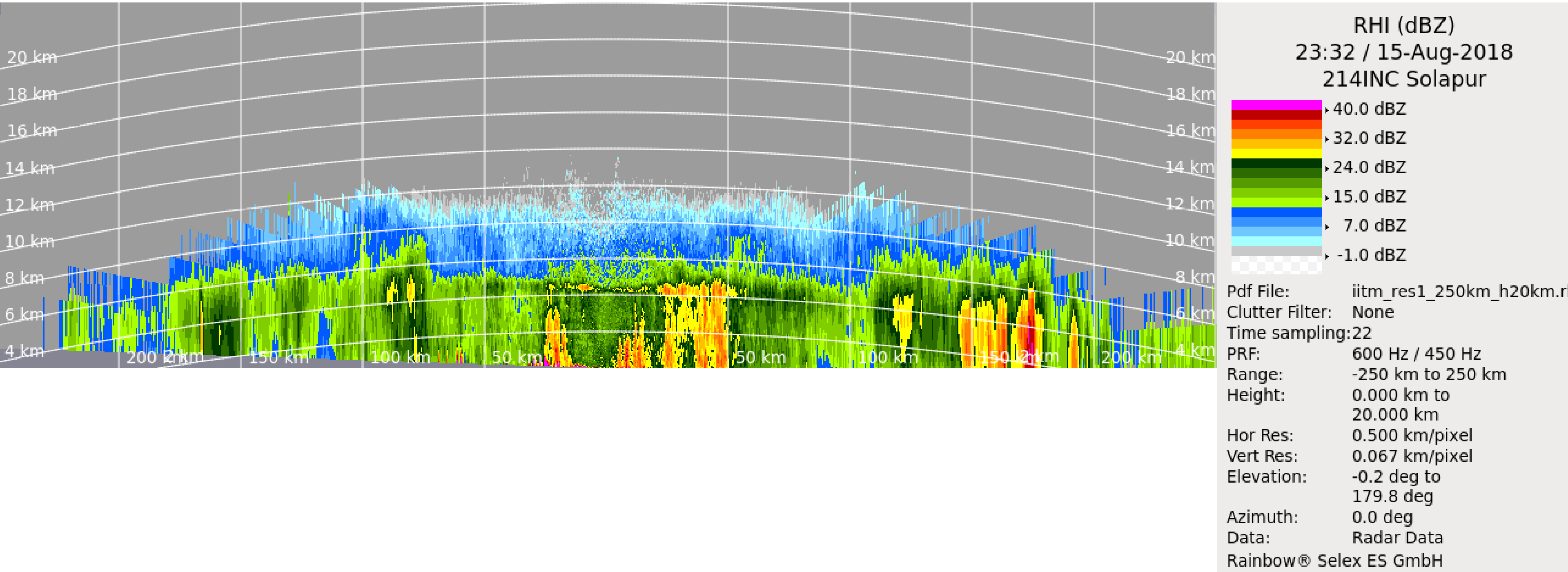
hydrometeors	size	terminal velocity
cloud droplets	< 100 µm	< 0.25 m/s
rain drops	100 µm – 8 mm	0.25 m/s – 4 m/s
ice crystals	< 1.5 mm	< 0.6 m/s
snow flakes	1 mm – 12 mm	0.5 m/s – 1.5 m/s
graupel	0.5 mm – 4 mm	0.75 m/s – 3 m/s
hailstones	5 mm – 8 cm	5 m/s – 50 m/s

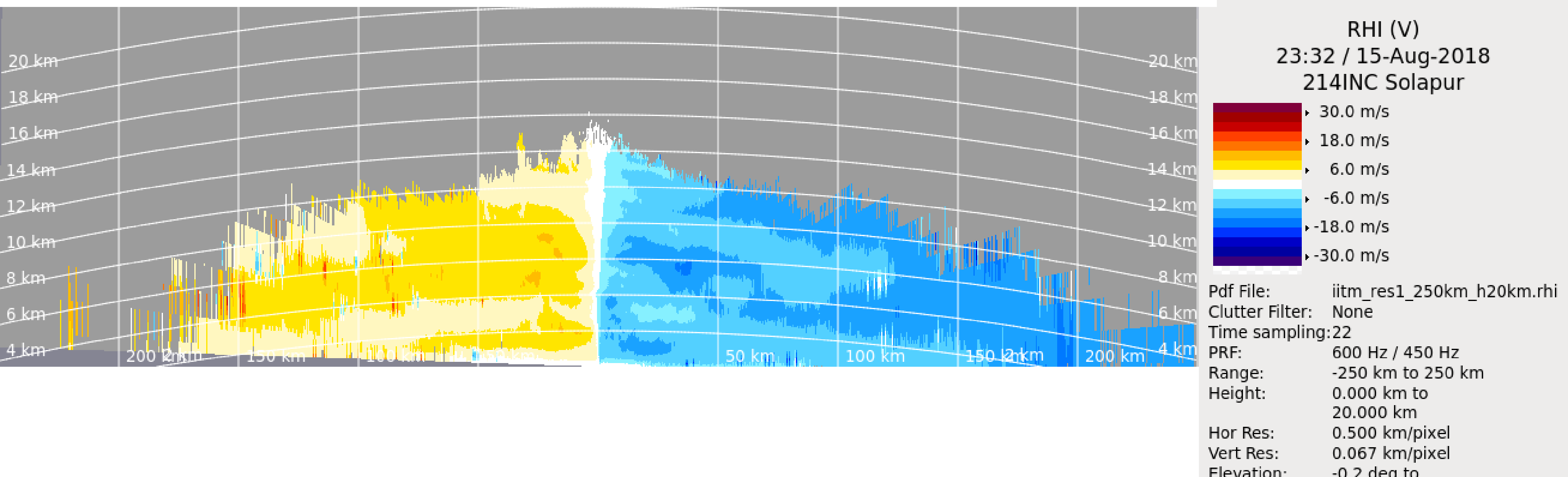
Houze [1993]

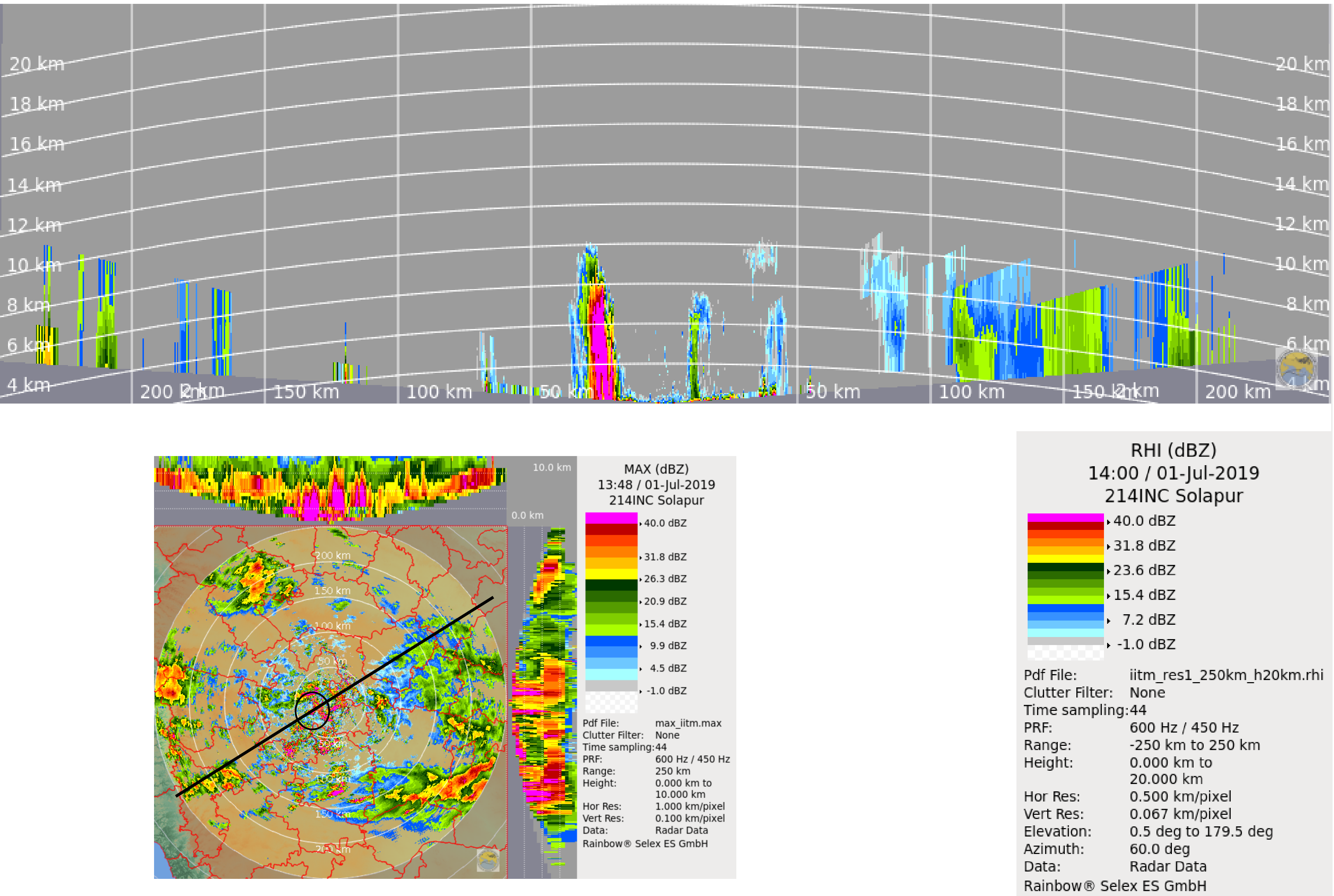
mixed-phase clouds	-30 to -10 dBZ
ice clouds	-25 to -10 dBZ
melting layer	-20 to 0 dBZ
marginally detectable precipitation	-20 to 0 dBZ
drizzle, very light rain or light snow	0-10 dBZ
moderate rain and heavier snow	10-30 dBZ
melting snow	30-45 dBZ
moderate to heavy rain	30-60 dBZ
hail	> 60 dBZ


PPI (dBZ)
23:26 / 15-Aug-2
214INC Solapu
40.0 dBZ
32.0 dBZ
26.0 dBZ
21.0 dBZ
15.0 dBZ
10.0 dBZ
4.0 dBZ
-1.0 dBZ
Pdf File: iitm_res1_2
Clutter Filter: None
Time sampling:22
PRF: 600 Hz / 45
Range: 250 km
Resolution: 1.000 km/p
Elevation: 1.5 deg
Data: Radar Data
Rainbow® Selex ES GmbH

RHI images of Reflectivity and Doppler products across the system 0 degree

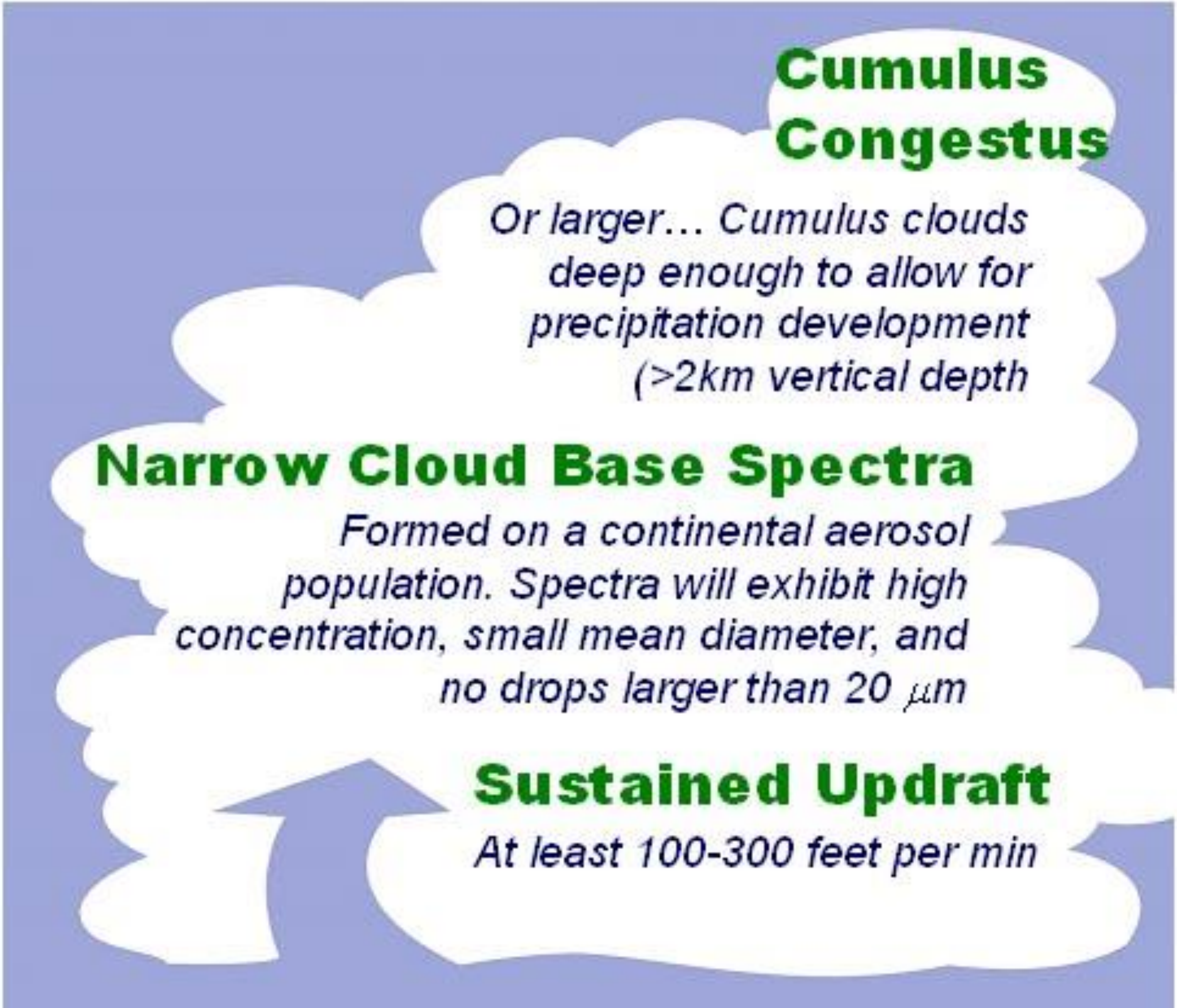




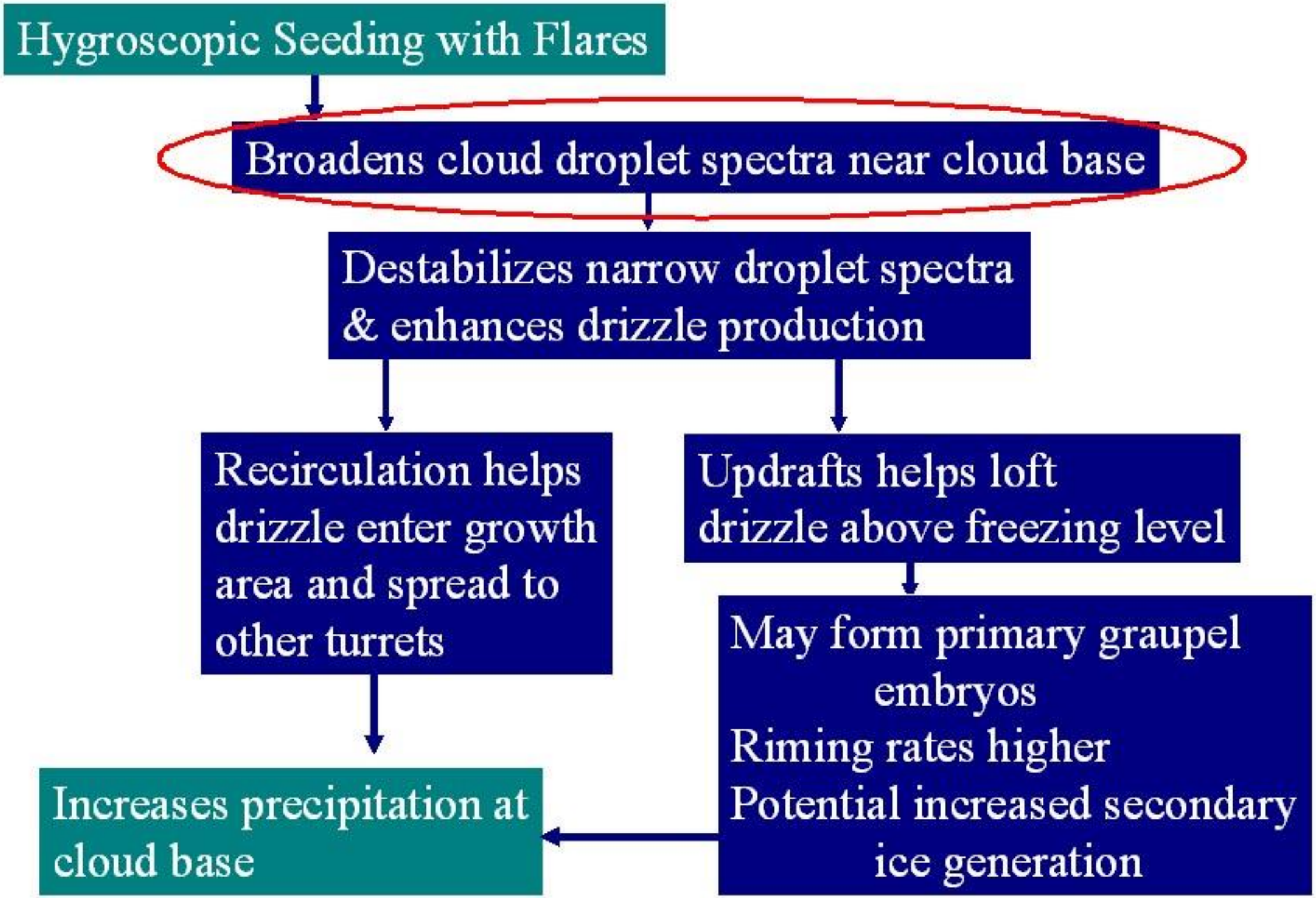

20 km
18 km
16 km
14 km
12 km
10 km
8 km
6 km
4 km
200 km
150 km
100 km
50 km
50 km
100 km
150 km
200 km
10.0 km
0.0 km
MAX (dBZ)
13:48 / 01-Jul-2019
214INC Solapur
40.0 dBZ
31.8 dBZ
26.3 dBZ
20.9 dBZ
15.4 dBZ
9.9 dBZ
4.5 dBZ
-1.0 dBZ
Pdf File: max_iitm.max
Clutter Filter: None
Time sampling:44
PRF: 600 Hz / 450 Hz
Range: 250 km
Height: 0.000 km to 10.000 km
Hor Res: 1.000 km/pixel
Vert Res: 0.100 km/pixel
Data: Radar Data
Rainbow® Selex ES GmbH
RHI (dBZ)
14:00 / 01-Jul-2019
214INC Solapur
40.0 dBZ
31.8 dBZ
23.6 dBZ
15.4 dBZ
7.2 dBZ
-1.0 dBZ
Pdf File: iitm_res1_250km_h20km.rhi
Clutter Filter: None
Time sampling:44
PRF: 600 Hz / 450 Hz
Range: -250 km to 250 km
Height: 0.000 km to 20.000 km
Hor Res: 0.500 km/pixel
Vert Res: 0.067 km/pixel
Elevation: 0.5 deg to 179.5 deg
Azimuth: 60.0 deg
Data: Radar Data
Rainbow® Selex ES GmbH

Hygroscopic seeding

- Applicable in clouds with tops below freezing level; warm clouds containing water droplets
- Hygroscopic material is dispersed into the updraft region at cloud base
- Particles are larger and more hygroscopic than the natural particles
- The cloud droplets nucleate preferentially on the seeding particles
- This inhibits smaller natural cloud condensation nuclei from becoming activated
- The result is a broader-than-natural droplet spectrum near cloud base
- Increases potential for precipitation to develop earlier and more efficiently in the lifetime of the cloud.


Cumulus Congestus
Or larger… Cumulus clouds deep enough to allow for precipitation development (>2km vertical depth
Narrow Cloud Base Spectra
Formed on a continental aerosol population. Spectra will exhibit high concentration, small mean diameter, and no drops larger than 20 μm
Sustained Updraft
At least 100-300 feet per min

Hygroscopic Conceptual Model



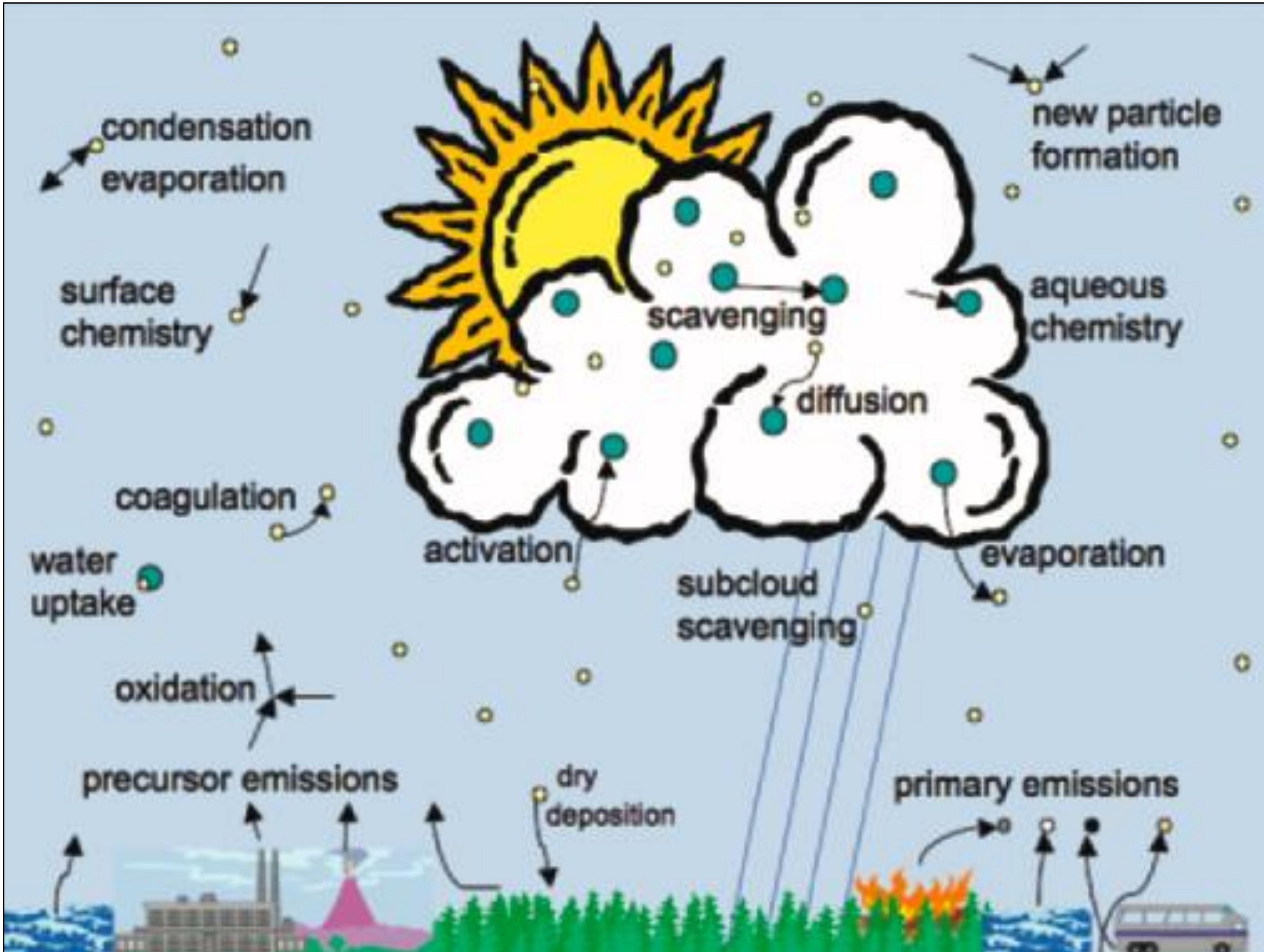
Glaciogenic seeding

- AgI is spread in the supercooled water region (deep cumulus, congestus).
- The ice crystals grow to the larger sizes and ultimately fall under gravity. While coming to earth they melt and produce the rainfall.
- Hypothesis is that a deficiency of natural ice nuclei and therefore insufficient ice particles (~1/liter at –20ºC) for the cloud to produce precipitation
- The natural clouds in their developing stages have ice concentrations <1 L^{-1} within their updrafts at the –5^{o}C to -10^{o}C level.
- AgI seeding initiates the ice process earlier in a cloud's lifetime.
- AgI seeding enhances the production of graupel earlier in a cloud's lifetime
- Graupel produced by AgI seeding provides more raindrop embryos
- Additional loading of precipitation at lower levels in seeded clouds results in changes in updraft/downdraft structures and modify dynamic aspects of the storm.

Cloud processing of aerosol

Clouds exert significant effects on aerosol

- Removal of aerosol by rain falling to the surface
- Convective redistribution
- Vertical transport of aerosol by clouds
- Coalescence processing (modification in the number and size of aerosol particles resulting from repeated drop coalescence events)
- Chemical processing (the formation of nonvolatile mass attributable to aqueous chemical reactions)
- New particle formation around clouds


condensation
evaporation
surface chemistry
coagulation
water uptake
oxidation
precursor emissions
scavenging
diffusion
activation
subcloud scavenging
dry deposition
new particle formation
aqueous chemistry
evaporation
primary emissions

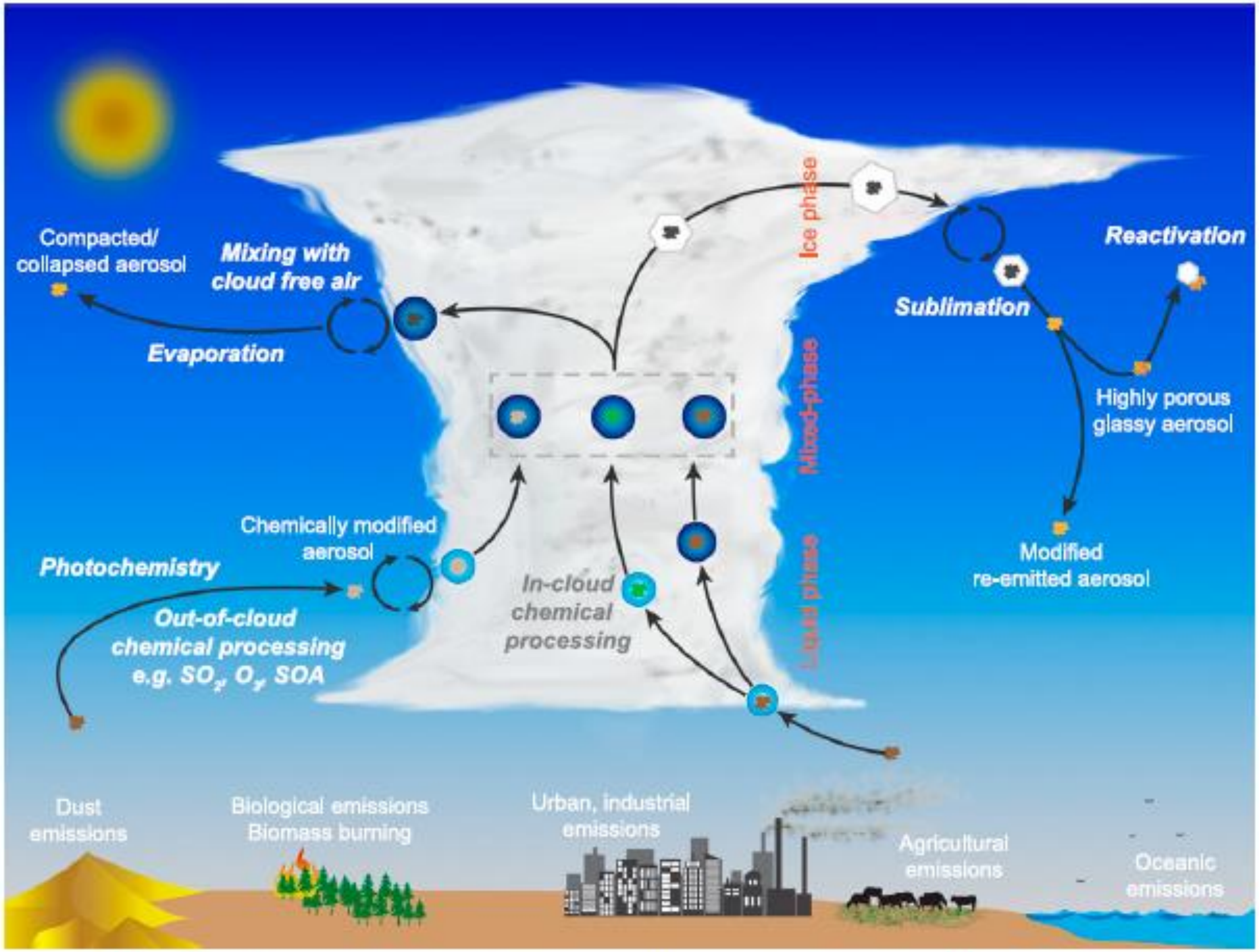


FIG. 1-9. Possible pathways of atmospheric processing and aging of aerosol discussed in this chapter (see section 4). The gray dotted box shows cloud droplets that could form via different aging pathways that can lead to modification of the aerosol. Different aerosol particle colors are to indicate that they have been modified compared to their emitted state. Bold lettering indicates processes and normal lettering, the presumed state of the aerosol resulting from indicated processes.